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Investigation To Enhance Load Monitoring For Resistance Training Exercises

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INVESTIGATION TO ENHANCE LOAD MONITORING FOR RESISTANCE TRAINING EXERCISES

TOM KINNERSLEY HULL

A thesis submitted for the degree of Master of Philosophy

University of Bath

Department for Health

October 2014

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ABSTRACT

Investigation to enhance load monitoring for resistance training exercises

Tom K. Hull, University of Bath, 2014

To optimise design and prescription of resistance training for elite athletes it is desirable to quantify their external training load. Volume load (barbell mass x repetition count) is the most widely used method, and despite its practical feasibility, may not be appropriately related to underlying mechanical principles, and does not account for displacement of body mass.

The aim of the study was to develop the scientific basis of commonly utilised resistance training quantification methods and propose a novel method, system mass volume load (SMVL). To address this aim, change in potential energy (ΔPE) was proposed as the mechanical underpinning of volume load and SMVL. The ΔPE of body mass was included in SMVL without the need for direct measurement by deriving a novel variable termed body mass factor.

Ten experienced resistance trained males performed 33 repetitions of the back squat and hang clean exercises on separate days with body segment and barbell kinematic data captured using CODA Motion scanners. Variation and systematic bias of barbell displacement, body segment ΔPE and body mass factor were determined between different barbell mass conditions (5 single repetitions at 70, 82 and 92 % of one repetition maximum) and over three sets of six consecutive repetitions (at 82 % of one repetition maximum). The degree of error in estimating the ΔPE of the whole system was also calculated to determine the accuracy of SMVL method.

For the back squat, estimation of the ΔPE of the whole system with known barbell displacement created an error of $0 \pm 8 \text{ J}$ ($0.0 \pm 0.7 \%$) and demonstrated an acceptable degree of accuracy. When barbell displacement was assumed constant, as required for the SMVL method, error was recorded as $2.5 \pm 3.5 \%$, representing an acceptable degree of accuracy for some individuals. Consequently, it is recommended to assess an individual's variation and systematic bias between barbell masses if direct measurements are not going to be routinely taken from the back squat. For the hang clean, strong significant bias in barbell displacement between conditions indicated use of the SMVL method with this exercise was not valid.

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NOMENCLATURE AND DEFINITIONS

ΔPE	Change in potential energy
1RM	One repetition maximum
BD	Barbell displacement
BMF	Body mass factor
BS70, BS82 or BS92	70 %, 82 % or 92 % of one repetition maximum barbell mass single repetition condition of back squat
BSS1, BSS2 or BSS3	First, second or third set of consecutive repetitions of back squat
CoM	Centre of mass
CV	Coefficient of variation
HC70, HC82 or HC92	70 %, 82 % or 92 % of one repetition maximum barbell mass single repetition condition of hang clean
HCS1, HCS2 or HCS3	First, second or third set of consecutive repetitions of hang clean
MDSVL	Maximum dynamic strength volume load
P#	Participant and their assigned number
PEW	Positive external work
RPE	Rating of perceived exertion
RT	Resistance Training
SMVL	System Mass Volume Load
TUT	Time-Under-Tension
VL	Volume Load

CHAPTER 1: INTRODUCTION

1.1. Research Overview

With continual improvement in sporting performance, along with the increasing social and monetary importance of results, optimising the training of elite athletes has never been of greater interest. Even the smallest of improvements have the potential to make the difference between success and failure. Therefore, to increase the chance of any athlete achieving their potential performance level, as well as minimising the risk of injury and overtraining, it is a high priority to quantify the relationship between training performed, subsequent responses, and the affect on sports performance.

As identified by Borresen and Lambert (2009), the first step in optimising the training of an athlete is to be able to quantify what is already done, otherwise interventions and their resulting impact cannot be appropriately evaluated and compared with alternatives. A crucial point in this process is determining which measurement metrics to utilise that are relevant to the intended outcome of training. For appropriate metrics to be selected, the relationships between training prescription, acute responses and resulting chronic adaptations need to be understood. It is considered that external training load (e.g. total mass displaced in a strength training session) elicits mechanical stimuli (Crewther et al., 2005) that in turn create internal training load (metabolic, structural, neural or hormonal stress; Lambert and Borresen, 2010). The internal training load then stimulates adaptation via physiological processes over either short or longer timescales (Lambert and Borresen, 2010). This conceptual model of the training process provides a framework for developing and selecting training quantification methods.

Resistance training (RT) is one of the most common modalities of training across elite, amateur and recreational athletes, and is characterised by displacing mass, often against the effect of gravity, with the goal of stimulating adaptation of the neuromuscular system. The external training load of RT is commonly designed to focus on development of maximum strength or power output and muscular hypertrophy. Many decades of experience from coaches, supported by an ever expanding body of empirical research, has established that training at around 70 % of one repetition maximum (1RM), or at 6-12RM, achieves hypertrophic adaptations (Campos et al., 2002, Crewther et al., 2005, Ratamess et al., 2009) whilst higher relative masses (85-100 % of 1RM, 1-6RM) should be used to elicit changes in the neural component of the motor

system (Häkkinen and Komi, 1983, Sale, 1988, Staron et al., 1991, Staron et al., 1994, Campos et al., 2002, Crewther et al., 2005, Ratamess et al., 2009). Recommendations for power training are more varied due to the diverse nature of possible training modalities. Recent reviews have concluded that, depending on exercise, 0-90 % of 1RM elicits the greatest adaptation (Cormie et al., 2011, McBride et al., 2011). The emphasis on design of training programmes to meet this goal is that the external load configuration utilised is related to outcome for which training is being undertaken. Despite this evidence base, guidelines for training prescription do not provide a quantitative metric of external training load and therefore are unable to robustly relate training performed to the processes leading to adaptation. Consequently, more detailed methods of RT quantification must be explored.

There are a range of methods proposed in the literature to quantify the external training load of RT, the most prevalent of these being volume load (VL), defined as the product of number of repetitions and barbell mass (Peterson et al., 2011). Some authors have described VL as an estimation of mechanical work during RT (Stone et al., 1999, Tran et al., 2006, Peterson et al., 2011) in trying to provide the mechanical link between training performed and subsequent responses. However, the theoretical basis or practical accuracy of this assertion has not been reported, and is reliant on the assumption that displacement is constant between repetitions of all RT exercises. An attempt was also made to incorporate body mass within the VL calculation (McBride et al., 2009), although this was subject to the same theoretical and practical short-comings as VL. Since the McBride et al. (2009) report was published, the efficacy of considering body mass with external mass in acute responses to RT has been demonstrated experimentally (Brandon, 2012). It was shown that when body mass was incorporated with maximum strength values, the acute responses to RT were normalised between individuals, where previously 1RM had been a distinguishing factor (Brandon, 2012), thus underlining the importance of body mass in training quantification.

Considering the lack of clarity provided by the current literature on methods to quantify RT, it remains an important area to investigate in the pursuit of greater optimisation of training. The major constraint is that methods must be practically feasible to be applied in every day training environments, without the need for expensive equipment or labour intensive data analysis. Achieving sufficient scientific validity within this practical context is a considerable challenge.

1.2. Statement of Purpose

The aim of this thesis was to develop the scientific basis of a practically feasible method of resistance training quantification whilst also examining the validity of a novel technique.

1.3. Research Questions

To meet the aim of this thesis, three main research questions were developed. These were designed to provide the first robust report of the accuracy of a currently used method of RT quantification (VL), and to explore the validity of a novel method of representing the action of the body within the quantification of load. Both of these areas of focus were addressed by examining change in potential energy (ΔPE) as an alternative metric for relating training quantity to the mechanical stimuli of RT. Inclusion of body mass using mechanically sound methodology has not been reported to date, and may represent a considerable improvement in accuracy and detail. For this approach to be valid and accurate, displacement of the barbell and ΔPE of the segments of the body would have to be assumed constant. In practical application, there are two possible sources of error relating to these assumptions, repetition-to-repetition variation and changes in magnitude of mean of a variable between sets. Therefore, to test their accuracy experimentally in two commonly used RT exercises (back squat and hang clean), the first research question was devised:

i. How do barbell displacement and ΔPE of the body segments vary between single repetitions at the same or different barbell masses?

Consecutive repetitions can cause changes in the kinematics of a movement sequence or reduce ability to continually execute to the technical specification (Duffey and Challis, 2007, Willardson et al., 2012, Hardee et al., 2013). As a result, the accuracy of the assumptions that barbell displacement (BD) and body segment ΔPE (body ΔPE) are constant at the same or different barbell masses were assessed in the absence of these effects of multiple repetitions. As many different barbell masses are frequently used in RT, and the training of elite athletes is specific to the individual, a number of sub-questions were proposed to examine three possible comparisons within the overall question:

- a) *What is the variation of BD and body ΔPE for an individual within a single barbell mass condition?*
- b) *What is the difference in magnitude and variation of BD and body ΔPE for an individual between barbell mass conditions?*
- c) *Is there a systematic difference in magnitude and variation of BD and body ΔPE for a group of participants across barbell mass conditions?*

These single repetition comparisons were designed to provide important information about participants' variation and bias due to barbell mass, but were not representative of the training of athletes. Therefore, research question two was proposed to include a training scheme similar to those used by athletes, thus allowing the greatest possible ecological validity from this cross-sectional investigation:

ii. How do barbell displacement and ΔPE of the body segments vary between three sets of consecutive repetitions at a moderately heavy barbell mass?

The majority of RT is performed in sets of consecutive repetitions. Consequently, the effect of this training structure on variation and systematic bias of BD and body ΔPE needed to be assessed. As with the first research question, specific sub-questions were devised to contribute to answering the overall research question:

- a) *What is the variation of BD and body ΔPE for an individual in a single set of consecutive repetitions?*
- b) *What is the difference in magnitude and variation of BD and body ΔPE for a group for a single set of consecutive repetitions in comparison to single repetitions at the same moderate barbell mass?*
- c) *What is the difference in magnitude and variation of BD and body ΔPE for an individual between three sets of consecutive repetitions?*
- d) *Is there a systematic difference in magnitude and variation of BD and body ΔPE for a group between three sets of six consecutive repetitions?*

The first two research questions directly measured the accuracy of individual assumptions for single and consecutive repetitions. The third research question was required to determine the practical effects of these assumptions when quantifying training load during a RT session representative of those performed by athletes. To achieve this aim, a novel standardised reference value that represented the ΔPE of the

body in relation to the barbell was proposed. It was termed the body mass factor (BMF), and it negates the need to directly measure displacement of the segments of the body to calculate their ΔPE . The BMF is incorporated in a modified version of VL that includes a proportion of body mass in the calculation of external training load. This new method is called system mass volume load (SMVL) and is representative of the ΔPE of the barbell and body mass. It led to the third research question:

iii. Can a standardised reference value (BMF) be used to calculate an accurate representation the ΔPE of the body segments in addition to the ΔPE of the barbell for the resistance training quantification method System Mass VL?

For the BMF value to be a practically useful tool in the training of athletes, it would have to be assumed constant either within- or between-individuals. If the level of accuracy of this assumption was acceptable, then the degree of error of using BMF in quantifying external load could be examined. As a result, five sub-questions were derived to answer the overall research question. The first three of these examined variation and systematic bias at and between different barbell masses. The final two sub-questions examined the level of accuracy that was achieved by calculations using only data readily available in a training environment:

- a) What is the variation of BMF for an individual within a single barbell mass condition?*
- b) What is the difference in variation and magnitude of BMF for an individual between barbell mass conditions?*
- c) Is there a systematic difference in magnitude and variation of BMF for a group of participants across barbell mass conditions?*
- d) How accurate is using the group mean BMF value from the single repetition condition with moderate barbell mass to estimate total ΔPE for consecutive repetitions?*
- e) Can a newly defined method of RT quantification (termed system mass VL) be used to calculate an accurate representation of total ΔPE for consecutive repetitions?*

In addressing the three main research questions and their associated sub-questions data were collected for the back squat and hang clean exercises. Results and discussion points are presented separately for each exercise with the overall thesis conclusions drawn across both.

1.4. Thesis Outline

Chapter 2: Literature Review

Previous research relevant to the area of RT quantification is examined in Chapter 2. Broadly, the topics covered are the basis of training monitoring of athletes, the fundamental principles of adaptation to RT, currently available methods, considerations around the use of the exercises in question for training elite athletes and finally statistical and measurement issues. The synthesis of the literature forms the basis from which the subsequent Chapters were designed and interpreted.

Chapter 3: Methodology

This Chapter describes the methodology utilised to address the research questions posed in this thesis. Kinematic data was collected from ten participants who performed 33 repetitions of each of the hang clean and back squat exercises. These repetitions were split between five singles performed at light (70 % of 1RM), moderate (82 % of 1RM) and heavy (92 % of 1RM) barbell masses followed by three sets of six consecutive repetitions at the moderate barbell mass. Data were analysed for barbell displacement, Δ PE of the segments of the body and a novel value termed body mass factor that represented the Δ PE of the body, relative to the barbell.

Chapter 4: Results

Variation and systematic bias of the derived variables were calculated between barbell mass conditions as well as between sets of consecutive repetitions. Additionally, estimates to the sum of barbell and body segment Δ PE were calculated using the body mass factor values. Comparisons were made at both the intra-individual and group levels.

Chapter 5: Discussion

The collected data is discussed in the light of the current literature and established theoretical basis for the project. Subsequently, the conclusions of the thesis are developed to specifically answer each of the posed research questions. The practical implications of this work are then considered, followed by directions for future research and finally the overall thesis conclusion.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

The first section of this literature review covers the basis for the quantification of athletes training and focuses on the mechanisms of neuromuscular adaptation to RT. The second section introduces the published evidence relating to currently available methods of quantification of RT. Finally, the third and fourth sections consider some of the methods employed in training elite athletes as well as measurement and statistical issues in determining the efficacy of methods used to quantify RT.

2.2. Training Load and Adaptation

2.2.1. Quantifying Training Load

The training of athletes can be considered as a dose-response process, where the ‘dose’ is the training undertaken by the athletes, and the ‘response’ is the resulting adaptation and subsequent performance change (Lambert and Borresen, 2010). The responses can be measured as the change sporting performance or in a laboratory/field test that assesses a particular aspect of an athlete’s physical capability. Conversely, it is a major challenge facing coaches and sport scientists to determine the most effective methods of quantifying the ‘dose’ experienced by athletes from the vast array of training modalities utilised across the sporting world. Indeed, it is this challenge that means for many commonly used training modalities there is little good quality published research describing the dose-response nature of their impact on sporting performance.

As further described by Lambert and Borresen (2010), the ‘dose’ that is prescribed by a coach or sport scientist can be done so at one of two levels. These are external or internal training load, and are dependent on the extent of knowledge of how any given training modality relates to subsequent adaptation (Figure 2.1). For example, an athlete performs a quantity of external training load such as the mass displaced in a RT session. This in turn elicits an internal training load which is the metabolic, structural, neural or hormonal stress experienced as a result of the external load. Subsequently, the internal training load stimulates adaption via physiological processes specific to the nature of the training (Figure 2.1; Spiering et al., 2008, Lambert and Borresen, 2010).

Consequently, methods of training quantification can either assess internal or external training load. The many methods that have been utilised across the literature can be further split into four categories: questionnaires and diaries, direct observations, physiological measures, and indices of training stress (Borresen and Lambert, 2009).

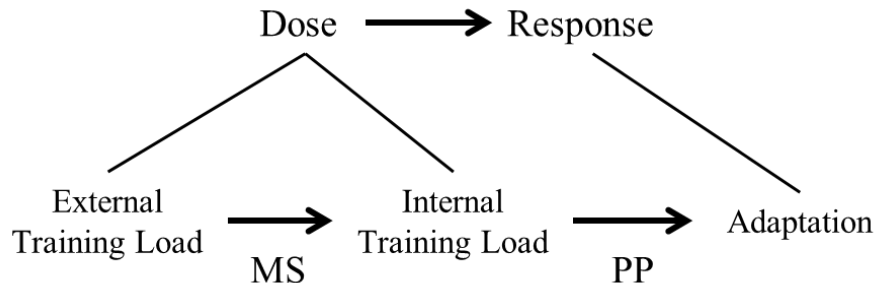


Figure 2.1. Conceptual model of the training process. MS = mechanical stimuli, PP = physiological processes. Information drawn from Crewther et al., (2005), Spiering et al., (2008) and Borresen and Lambert (2009).

Questionnaires and diaries can offer effective and logistically viable methods of data collection, although they are reliant on self-reporting, and their accuracy is determined by the athletes' ability to recall information reliably. Questionnaires are often administered weekly, monthly or yearly (Borresen and Lambert, 2009), and this limits the resolution of the information that they produce. Other confounding factors such as interpretation of questions asked, environmental factors at time of training and structure of questionnaire can affect the quality of results (Borresen and Lambert, 2009). Questionnaires have potential to provide accurate information but are inappropriate for determining external or internal training loads. Diaries on the other hand, are commonly used to monitor training content as well as athlete feelings of fatigue, readiness to train, quality of sleep and well-being. Recording of training content, depending on method used, provides information that can be fed into other methods of training quantification such as physiological measures and direct observations. Additionally, information gathered by training diaries can be valuable in determining athlete fatigue status and readiness to train. Overall, diaries can prove effective tools in monitoring of athlete status and quantification of training, although what information, and how it is gathered, is key to this process.

Direct observations can be used to quantify training performed in almost any modality. This involves information being recorded about exercise mode, duration, intensity, speed or repetition count and is dependent on the type of training being recorded

(Borresen and Lambert, 2009). They are prevalent in almost all sporting situations where the prescription modality is based on these observations and evaluated as such. For example, a running session may be prescribed in terms of distance at a given speed or a RT session may be prescribed in terms of repetitions at a given external mass (Kraemer et al., 1996). Direct observations are measures of external training load and require knowledge of their relationship with internal training load and either subsequent physical adaptations, or performance, to validate their use (Lambert and Borresen, 2010). When physiological measures are available for a particular training modality these can be combined with direct observations to provide information on the relationship between external and internal training load. If stable relationships can be established then training can be prescribed and evaluated based only on direct observations, but with knowledge of the internal training load experience by the athlete.

Many physiological measures have been proposed that either quantify an aspect of internal training load or the physiological processes resulting in adaptation. Heart rate is possibly the physiological measure that has received most attention, with it being widely used as a descriptor of continuous exercise intensity (Achten and Jeukendrup, 2003, Borresen and Lambert, 2009). For RT, where heart rate is not an appropriate measure, the effects have been quantified using systemic protein concentrations such as creatine kinase (McKune et al., 2012). Whilst this measure is appealing, it is subject to several confounding factors and high variability (McKune et al., 2012), meaning its use as a stable marker of internal training load is not possible. Advances in physiological measurements of RT to determine internal training load must be matched by appropriate quantification of external load to allow more informed training prescription.

Finally, indices of training stress attempt to combine physiological measurements with direct observations to calculate the internal training load experienced by an athlete. Session rating of perceived exertion (RPE) is an index that is both practically feasible and reliable when quantifying high intensity training, such as RT (Gearhart et al., 2001). This method takes the athletes self-perception of the intensity of training and multiplies it by the length of the session in minutes. It is an easy to collect and interpret measure that has been found to be related to exercise intensity (Sweet et al., 2004), as well as being important in monitoring for overtraining (Foster, 1998).

Any training intervention is intended to contribute towards improving sporting performance. However, it must also be considered that the response may be detrimental.

In the short-term, this is an established feature of training, resulting in super compensation, although an imbalance in prescribed training and the requirement for recovery for prolonged periods can have serious consequences. Indeed, inaccuracy in prescribing training for athletes has been considered a contributing factor to the condition of overtraining (Borresen and Lambert, 2009). Therefore, another key aspect of the quantification of training is being able to determine the over-dose that leads to a response that is detrimental to performance in long run.

It is highly unlikely that accurate dose-response relationships will be able to be robustly determined for many training modalities due to the wide range of confounding factors. Consequently, it is of increased importance that the interaction of external and internal training load is understood to inform the design of training interventions for maximising performance. Refinement of the measurement methods at all levels of this process is constantly occurring in the sports science field, although some areas are underrepresented in the published research. Indeed, the physiological quantification of high intensity training modalities, such as RT, is limited by the invasive nature of the measures required to quantify internal load. (Kraemer and Ratamess, 2005, Folland and Williams, 2007). Therefore, a much greater reliance on direct observations is necessary, although further investigation in the laboratory setting is required to develop the necessary measurement methods.

2.2.2. Resistance Training Overview

Outside of training specific to an athletes' sport, RT is one of the most commonly utilised modalities to improve sporting performance (Cormie et al., 2011). The prevalence of RT is largely due to the improvements seen in a wide range of neuromuscular performance characteristics after periods using this type of training (Cormie et al., 2011). These improvements have been shown to transfer to sports specific performance indicators such as speed, agility, strength and jump height. In addition, RT can also be utilised for manipulating body composition, rehabilitation and injury prevention. The extent to which RT is utilised for elite athletes is dependent on the physical requirements of a particular sport and how these relate to the many possible outcomes of RT. Despite the well-established efficacy, the literature is far from comprehensive in understanding relationships between external and internal training load for RT.

The term RT is a very broad one, appearing frequently within the literature and often used interchangeably with other terms such as strength training. It is best to consider RT as an umbrella term under which sits an array of different modalities. Simply, RT stimulates physical adaption by repeated exposure to a demand that overloads the neuromuscular system. The overload is created by the external training load and this leads to internal training load which temporarily disrupts an individual's physiological status (reduction in performance). When allowed to recover, the body then undergoes a super compensation that prepares the neuromuscular system for a repeated exposure to the original stimuli by improving its performance capability (Meeusen et al., 2006). By progressively increasing the overload, adaptation is continually promoted. The external and internal training load can be considered either acute (i.e. that delivered by a single session) or chronic (i.e. that delivered over time by a combination of sessions) and is dictated by RT session structure. Careful manipulation of load, combined with sufficient recovery, is required to provide the optimal training dose for athletic development whilst maintaining the well-being of the athlete.

Design of RT sessions is based on a number of factors, termed acute programme variables (Kraemer et al., 1996), and these have been defined as choice of exercise, order of exercise, resistance or intensity used, number of sets and repetitions, and rest periods. Within each of these acute programme variables are many more factors to be considered in determining the specific training load experienced by an individual (Fry, 2004). For example, choice of exercise will consider: prime movers, co-contractors, joint ranges of motion, movement sequence, movement intention, movement velocity and the duration of muscle contraction. These factors are further confounded by the effect of periodisation of RT programmes, that is, how the acute programme variables are manipulated over time (Fry, 2004).

The three most frequently utilised distinct RT session types are those focused on developing maximum strength or power output of the neuromuscular system and hypertrophy of muscle. These types of training can be characterised by differences in the acute programme variable manipulations employed in their design. Increases in maximum strength are predominantly attributed to greater cross section area of muscle (hypertrophy) as well as improvement in neural control factors, such as motor unit recruitment. It is generally accepted that training at around 70 % of an individuals' one repetition maximum external mass (1RM), or at 6-12RM, achieves hypertrophic adaptations (Campos et al., 2002, Crewther et al., 2005, Ratamess et al., 2009) whilst

higher relative masses (85-100 % 1RM, 1-6RM) should be used to achieve neural adaptations (Häkkinen and Komi, 1983, Sale, 1988, Staron et al., 1991, Staron et al., 1994, Campos et al., 2002, Crewther et al., 2005, Ratamess et al., 2009). Training with different relative intensities requires changes in the number of sets and repetitions being utilised, with hypertrophy programmes typically containing more total repetitions than sessions designed for neural adaptations.

Considerably more debate exists around best practice in the development of maximum power output. A body of research has suggested that training at the relative intensity where maximum power output occurs (0-90 % 1RM, depending on exercise) elicits the greatest adaptive response (Cormie et al., 2011, McBride et al., 2011). However, others have recommended training at 30-50 % of 1RM (Crewther et al., 2005) or 0-30 % of 1RM (Cormie et al., 2010), whilst the American College of Sports Medicine recommendations capture the broad range of findings by recommending 0-60 % of 1RM (Ratamess et al., 2009). Despite these conflicting reports, power output training methodologies always incorporate the intent to perform the exercise as quickly or explosively as possible. Due to the complex nature of the factors contributing to increased neuromuscular power output, including load and exercise selection, a narrow definition of the available training modalities is not possible. Consequently, whilst maximum strength and hypertrophy training can be clearly delineated by the acute programme variables, power training is defined by the intent to maximise movement velocity (Brandon, 2012).

2.2.3. Adaptation of the Neuromuscular System to Resistance Training

As stated, the basic premise of RT is to overload the demands placed on the neuromuscular system to stimulate adaptation. The basic functional unit of the neuromuscular system is the motor unit and this consists of a motor neuron that innervates a group of muscle fascicles which contains the contractile elements. As a result, the adaptations that are elicited by RT can be split into morphological (those concerning the structure of the fascicles) and neural changes (those concerning innervation via the motor neuron; Folland and Williams, 2007). This conceptual splitting of the neuromuscular system can be seen in much of the research examining the chronic responses to RT, with many authors focusing on one aspect.

Morphological adaptations to RT are typically elicited by ‘hypertrophy’ type training. The acute programme variable manipulations utilised lead to RT sessions of multiple sets at an external mass of around 6-12RM (Staron et al., 1991, Staron et al., 1994, Marx et al., 2001, Campos et al., 2002, McBride et al., 2003, Crewther et al., 2005, Ratamess et al., 2009). Due to the importance of the contribution of physiological cross-sectional area of muscle to maximal force production (Fukunaga et al., 2001), training for morphological adaptations to RT is common among athletic populations. However, despite the cellular and molecular pathways leading to increased muscle protein synthesis being well established, there remains considerable ambiguity in best practice for achieving this *in vivo* (Spiering et al., 2008).

The review of Spiering et al. (2008) identified that description of the relationship between acute programme variables and morphological adaptations to RT in the literature was far from comprehensive. Although, considering the acute programme variables are only descriptions of the structure of an RT session, a direct link with adaptation is not entirely surprising. The concept of the ‘mechanical stimuli’ of RT discussed by Crewther et al. (2005) could explain the discrepancy. The mechanical stimuli of RT are proposed to be the kinetic or energetic aspects of the exercise performed that link the external training load (i.e. that described by the acute programme variables) with the internal training load (i.e. the subsequent response of the body that elicits adaptation to a given stimuli; Figure 2.1). Indeed, mechanical stimuli could be considered to be the aspect of exercise that initiates the systemic responses and resultant cascade leading to functional adaptation in the theoretical model presented by Spiering et al. (2008). Therefore, if improved relationships are to be identified between acute programme variables that are known to influence morphological adaptation to RT, then the mechanical stimuli elicited by external training load must be considered.

Neurological adaptations to RT have been described as changes in coordination and learning that allow greater activation and recruitment of muscle fascicles in a task specific manner (Folland and Williams, 2007). A number of distinct neural adaptations were identified by the review of Folland and Williams (2007), and included firing frequency, synchronisation, cortical adaptations, spinal reflexes and antagonist co-activation. Both Duchateau et al. (2006) and Folland and Williams (2007) concluded that whilst a considerable evidence base exists that creates little doubt that neurological changes occur as a result of RT, the evidential basis for links between RT performed and specific adaptations is poor.

Studies that have reported data demonstrating neurological adaptations to RT have used a variety of measurement methods. Peripherally, surface electromyography has been shown to be related to increases in force production (Häkkinen and Komi, 1983, Narici et al., 1989, Häkkinen et al., 2003), although the methodological issues with this technology prevent conclusive evidence being obtained. As well as magnitude of neural activation, motor unit firing frequency has also been shown to increase with RT, leading to greater force output (Van Cutsem et al., 1998, Duchateau et al., 2006). Besides differences in the signal that innervates muscle being shown, reflexes have been used to demonstrate increases in motor neuron excitability and central drive, coupled with decreases in post synaptic inhibition after high intensity RT (Aagaard et al., 2002a, Aagaard et al., 2002b). Overall, it can be seen that changes occur at all levels of the neural system, although specific composition of the RT required to elicit these changes is not entirely clear.

The detailed consideration of the acute programme variables that is required to form definitive conclusions on prescription to achieve the many neural adaptations to RT has not been presented in the literature. What is common among many studies in this area is the use of high intensity and maximal effort RT (Häkkinen and Komi, 1983, Narici et al., 1989, Aagaard et al., 2002a, Aagaard et al., 2002b, Häkkinen et al., 2003), suggesting that high external mass is required to elicit these changes. However, considerable effects have also been found using only 30-40 % of 1RM (Van Cutsem et al., 1998), although this training was still performed with maximal intent. Despite some conflicting evidence, authors who have reviewed the area have highlighted the importance of high relative intensity or intent of RT required to achieve neural adaptations (Duchateau et al., 2006, Folland and Williams, 2007) and this has been reflected in prescription recommendations (Ratamess et al., 2009).

Even for the morphological or neural adaptations that are best supported in the literature, there are not comprehensive descriptions of the specific acute programme variable manipulations required over time to optimise neuromuscular force production gains from RT. To continue developing understanding of the extremely complex processes resulting in adaptation from RT, external training load must be quantified using a method that is related to the mechanical stimuli that elicit internal training load. In addition accurate quantification of training load is required to prevent over exposure and the subsequent negative consequences.

2.2.4. Overtraining

Overtraining is a term that appears frequently in the scientific literature relating to the training of athletes. It refers to a physiological condition induced by stressors experienced by the athlete, resulting in long-term decreased performance and fatigue (Halsen and Jeukendrup, 2004). It is hypothesised that the state of overtraining is induced by an intensified period of training where recovery is inadequate to offset the physical and psychological stress experienced (Urhausen and Kindermann, 2002, Halsen and Jeukendrup, 2004, Kellmann, 2010). Beyond decreased performance and prolonged fatigue, overtraining is reported to be associated with muscle soreness, overuse injuries, reduced appetite, disturbed sleep patterns, mood disturbances, immune system deficits and concentration difficulties (Kellmann, 2010).

Despite the frequency of attention, the concept of overtraining is supported only by anecdotal evidence (Urhausen and Kindermann, 2002, Halsen and Jeukendrup, 2004). This is due to the prohibitive difficulty of obtaining high quality data from athletes experiencing the condition. Unsurprisingly, ethical approval may be difficult to obtain for controlled investigations because of the wide range of negative symptoms associated with overtraining. Consequently, the evidence base is comprised of reports of incidences of this condition in individual athletes which are lacking consistency of objective measurement. Furthermore, as highlighted by Halsen and Jeukendrup (2004), there are no diagnostic tools to determine overtraining and as such, a diagnosis can only be made on the basis of ruling out all other confounding factors for the decreased performance or inability to recover.

There has been considerable discussion in the literature surrounding the conceptual model of overtraining. It has been suggested that overtraining sits at one end of a continuum based on the level of fatigue and severity of symptoms (Fry et al., 1991, Halsen and Jeukendrup, 2004). At the opposite end of this continuum is the fatigue and recovery required from a single training session, with the intermediary stage being the condition termed overreaching. Overreaching has been considered as the precursor to overtraining by numerous sources (Fry et al., 1991, Fry and Kraemer, 1997, Kentta and Hassinen, 1998, Urhausen and Kindermann, 2002, Halsen and Jeukendrup, 2004) and is defined as a short-term decrement in performance that takes days to weeks to recover from, as opposed to several weeks to months for overtraining. However, the lack of an evidential basis makes the continuum model difficult to validate. Indeed, the operational

definitions used by Halson and Jeukendrup (2004) indicate the difference between the conditions is the time taken to recover, rather than their root causes. What is clear from the literature is that both overtraining and overreaching are products of training stressors and mechanical stimuli putting the body into an increasing state of fatigue, with inadequate time to recover. As such, the basic initiator of the two conditions being training stress exceeding recovery over a period of time is similar, however, the mechanisms of their occurrence and the impact of psychological factors remain unclear. Indeed, overreaching could well be part of the normal training process that occurs due to progressive overload, which in turn results in super compensation and performance increases (Halson and Jeukendrup, 2004, Meeusen et al., 2006). This manifestation of overreaching has been termed functional overreaching and is considered a common component of the training of elite athletes (Meeusen et al., 2006). If a period of elevated training continues without adequate recovery then non-functional overreaching can occur where performance stagnates or decreases, although athletes in this situation will recover given sufficient time (Meeusen et al., 2006).

As succinctly summed up by Meeusen et al. (2006), training that is successful is that which provides a stimulus that overloads the body but avoids excess with concurrent inadequate recovery in the long run. Therefore, in attempting to effectively achieve the required overload, whilst avoiding the unwanted conditions of non-functional overreaching and overtraining (i.e. optimising the ‘dose’ without a negative ‘response’), training must be accurately quantified and moderated accordingly. Unfortunately many investigations in this area don’t report quantity of training or athlete responses to variations in training intensity/quantity on an intra- or inter-individual basis. To improve the quality of the empirical evidence base into overtraining it is important that external training load and its systemic affects are accurately quantified.

2.3. Applied Methods of Quantifying Resistance Training

2.3.1. Number of Repetitions

Number of repetitions is the term used to describe the total number of repetitions of a RT exercise(s) performed in a given training period. It is one of the most readily manipulated acute programme variables in empirical investigations and the applied training setting. It is also the simplest method of quantifying the amount of RT

performed by an individual, as it merely requires repetitions to be counted. In the literature, the number of repetitions is often referred to as ‘volume’ or ‘training volume’ (Häkkinen and Pakarinen, 1991, Fry et al., 1994, Fry et al., 2000, Crewther et al., 2011). The alternate terminology of number of repetitions is chosen here as ‘volume’ is an ambiguous term that can be interpreted in many ways when describing quantity of RT performed.

Determining the number of repetitions as a method of quantifying RT has received considerable attention in the literature due to its practical feasibility. The majority of studies have examined how one or more physiological responses are affected by manipulations in the number of repetitions performed. These responses have included neuromuscular strength and power adaptations (Marx et al., 2001, McBride et al., 2003, Ronnestad et al., 2007, Marshall et al., 2011), muscular hypertrophy (Ronnestad et al., 2007, Wernbom et al., 2007), hormonal fluctuations (Häkkinen and Pakarinen, 1991, Fry et al., 1994, Fry et al., 2000, Marx et al., 2001, Crewther et al., 2011) and changes in body composition (Marx et al., 2001, McBride et al., 2003). Many of the studies discussed have manipulated the number of repetitions, resulting in concurrent alterations in other acute programme variables. It is, however, impossible to alter the number of repetitions without other acute programme variables changing, thus demonstrating their fundamental integration.

There have been many investigations focusing on whether one or multiple sets of repetitions of RT exercise(s) elicit greater improvements in neuromuscular force production. Reviews, such as those of Carpinelli and Otto (1998) and the meta-analysis of Krieger (2009), have summarised the area, although findings have been conflicting. Carpinelli and Otto (1998) concluded that multiple sets were not more beneficial in the development of neuromuscular force output compared with single sets. Thus, this suggests that change in the number of repetitions was not able to reflect neuromuscular adaption. However, extensive work has been conducted in this area since the publication of the Carpinelli and Otto (1998) paper, much of which has concluded in favour of greater neuromuscular strength gains from multiple sets (e.g. McBride et al., 2003, Munn et al., 2005, Ronnestad et al., 2007). Indeed, the more recent review of Krieger (2009) concluded that multiple sets of repetitions can lead to 48 % greater neuromuscular strength gains than one set of repetitions in both trained and untrained participants.

Unfortunately, the applicability of the evidence reviewed by Krieger (2009) to inform the RT of athletes is limited. Much of the data have been collected using participants not from athletic populations (i.e. they were untrained or low training age). The responses to structured RT interventions will be considerably different between nonathletic individuals and athletes (Evans et al., 1986), meaning the data do not greatly inform the current discussion. Additionally, many of these studies are conducted using experimental designs that compare one or three sets of repetitions, and thus they are not representative of RT performed by athletes (Cormie et al., 2011).

A recent report published by Marshall et al. (2011) does provide evidence for the efficacy of quantifying the number of repetitions in relation to RT prescriptions that increase neuromuscular force production. Comparisons were made between one, four and eight sets of repetitions of back squats to failure at an intensity of 80 % of 1RM twice per week. The training period was 10-weeks and measures of barbell back squat 1RM, quadriceps muscle activation and contractile rate of force development were taken at three, six and ten weeks. The results indicated that the strength increases of the group performing eight sets were significantly greater than the group performing one set at all points after baseline (squat 1RM increase 37.0 vs. 17.4 kg by week 10; Marshall et al., 2011). The data also suggested that the group performing four sets per session saw an increase in strength above those performing one set, although this difference did not reach statistical significance. The same was the case when the four set group was compared with the eight set group, the latter showing the largest increases. The strength of this study is that the selected acute programme variables were more comparable to the training of athletes. The squat is one of the most commonly utilised exercises for RT aimed at increasing sporting performance. Moreover, the number of sets utilised by Marshall et al. (2011) was more comparable to those seen in elite training environments, as opposed to some other studies (Carpinelli and Otto, 1998, McBride et al., 2003, Ronnestad et al., 2007).

There have been a range of effects found by investigations into fluctuations of the number of repetitions on hormone responses to RT sessions (Häkkinen and Pakarinen, 1991, Fry et al., 1994, Fry et al., 2000, Marx et al., 2001, Crewther et al., 2011). The Fry et al. (1994) investigation showed that not only can the number of repetitions influence hormonal response to exercise, this is affected by the training status of the individual as well. Further work from the same group found that the number of repetitions was a confounding factor on the correlation between pre-RT

testosterone:cortisol ratio and weightlifting performance (Fry et al., 2000). They went on to conclude that, compared with less skilled athletes, the weightlifting performance of the elite lifters was more sensitive to reduction in number of repetitions following the previous period where the number of repetitions performed was higher (Fry et al., 2000). In contrast, the investigations by Häkkinen and Pakarinen (1991) and Crewther et al. (2011) demonstrated that using the number of repetitions as a means of quantifying RT was not able to detect manipulations in acute training variables that led to altered hormonal responses.

Across the literature, manipulation of the number of repetitions has been shown to cause fluctuations in a wide range of acute and chronic responses to RT. However, this method does not quantify external training load in relation to the mechanical stimuli of RT. Consequently, it is highly unlikely to be able to detect sensitive relationships between dose and response. Indeed, the summary of Wernbom et al. (2007) highlights this issue well. Having conducted an extensive review, they concluded that typically RT sessions of 30-60 repetitions led to the greater hypertrophic adaptations. However, when the intensity of RT is increased (up to 230 % 1RM) only 12-14 repetitions were required to achieve similar gains (Wernbom et al., 2007). If additional acute programme variables or information regarding the specific mechanical demands of RT are incorporated with the number of repetitions then sensitivity should improve.

2.3.2. Volume Load

An extension of counting the number of repetitions is the volume load (VL) method. It incorporates another acute programme variable, external mass, and is calculated as the product of these two quantities. The cumulative sum of VL produces a value representing the total external mass lifted in all repetitions over a given training period. As identified by Peterson et al. (2011), VL is one of the most widely accepted measures of the quantity of RT performed, although this is against a backdrop of considerable debate. The VL measure has been employed in a variety of experimental designs within the literature. For example, it has been used as an independent factor in comparisons with other measures to determine training effects (Häkkinen et al., 1987, Haff et al., 2008, Peterson et al., 2011) and to equate quantity of training in different protocols (Tran and Docherty, 2006, Crewther et al., 2008, Kok et al., 2009, McBride et al., 2009). Furthermore, it has been directly manipulated to establish its affect on neuromuscular fatigue (Tran et al., 2006). Despite this popularity, it is difficult to draw

conclusions on the relationship between VL and neuromuscular responses to RT from these studies due to their diverse nature. Additionally, VL has been considered to be representative of mechanical quantities such as work (Stone et al., 1999, Tran et al., 2006), although this is subject to several assumptions, the efficacies of which are yet to be investigated.

Whilst examining elite weightlifters, both Häkkinen et al. (1987) and Haff et al. (2008) reported data showing that blood hormonal concentrations (possible indicators of anabolic status; Kraemer and Ratamess, 2005) were related to manipulations in VL. Neuromuscular performance measures were also investigated by Haff et al. (2008) and they demonstrated that isometric peak force was influenced by manipulations in VL of more than 30 % and hypothesised that this could have an impact on an athletes' preparedness for competition (Haff et al., 2008). Together, these studies demonstrate correlative data supporting the acute sensitivity of neuromuscular and hormonal responses to fluctuations in VL, although this relationship cannot be conclusively determined to be causative.

The study of Tran et al. (2006) made a direct assessment of the specific effect of VL on acute neuromuscular responses to RT. The authors compared three experimental conditions where VL and time-under-tension (TUT; sum of eccentric contraction time and concentric contraction time – see Section 2.3.5) were manipulated independently, with markers of acute neuromuscular fatigue measured. The results showed that reduction of either VL or TUT, whilst the other remained constant, led to altered acute neuromuscular fatigue responses, thus demonstrating that both measures should be considered in RT stimulus. Therefore, over time it could be hypothesised that two training protocols matched for VL could lead to different neuromuscular adaptations.

Peterson et al. (2011) examined the predictive ability of VL to detect changes in muscle strength and hypertrophy in an active mixed gender population over a 12 week training programme. Measures of neuromuscular performance and hypertrophy were taken pre- and post-training, whilst VL was calculated for the whole period. In contrast to the potential insensitivity of VL shown by Tran et al. (2006), VL was strongly and independently associated with the change in 1RM for both male and female participants (Peterson et al., 2011). As such this study is unique in identifying the discrete influence of VL on neuromuscular adaptation to RT. However, the findings of Peterson et al.

(2011) need to be replicated in an athletic population utilising more representative training methods to confirm the applicability of these results on such a population.

The study of McBride et al. (2009) is the only direct attempt at assessing the accuracy of VL as a measure of quantity of RT that has been found in the literature. Comparisons were made between three different exercise protocols (strength, hypertrophy and power) using four different RT quantification methods. The measurement techniques were VL, maximal dynamic strength volume load (MDSVL; VL with a proportion of body mass displaced through the exercise included in total mass – see Section 2.3.3), TUT and mechanical work (area under force-displacement curve – see Section 2.3.4). Significant differences in training quantity recorded for each condition led to the conclusion that VL was an invalid measure of the overall training load due to it being unable quantify RT with no external mass. However, there was no gold standard measure used to suggest each condition should be equal in training quantity. Considering the vastly different acute programme variable structures and mechanisms for adaptation for each of the training focuses, it would appear logical to expect differences in external training load. Consequently, the attempt of McBride et al. (2009) to compare various methods of quantifying RT does not offer an experimental design from which conclusions on their validity can be drawn.

An important issue that has not been addressed is lack of a definition of what aspect of external training load that VL is quantifying, and how this relates the mechanical stimuli of RT. Both Stone et al. (1999) and Tran et al. (2006) contend that VL is an estimation of mechanical work. However, the accurate measurement of mechanical work during human movement is theoretically and practically difficult (see Sections 2.3.4 and 2.5.1 for more detail). The complexity of this area is not reflected in the calculation of VL and thus it is inappropriate to use this definition. Despite this misconception of other authors, VL does provide a description of the displacement of mass against the action of gravity. This is subject to the yet-to-be-validated assumption that barbell displacement is constant between repetitions, although this is supported by the authors proposing mechanical work as the basis of VL (Stone et al., 1999, Tran et al., 2006). It is plausible to assume that for an individual who is very experienced in RT, barbell displacement may show very low variation between repetitions. However, there is no data published supporting this or describing the variability of barbell displacement, so the degree of error that this assumption creates is unknown.

Another methodological issue with VL is that it does not account for the requirement to displace body mass against the effect of gravity. It has been shown that consideration of an individual's body mass within their 1RM (sum of external mass and body mass) accounts for observed differences in acute neuromuscular response to RT seen between individuals when only external mass is considered (Brandon, 2012). Moreover when the percentage of total maximum load lifted (inclusive of external mass and body mass) was matched between individuals of varying absolute maximum strength no differences were detected in acute neuromuscular responses (Brandon, 2012). These data indicate that the body mass of individuals performing RT is a confounding factor on neuromuscular response, especially when RT intensity is prescribed relative to total maximum strength levels.

Evidence for relationships between manipulations in VL and acute neuromuscular and physiological responses to RT are conflicting. This is likely due to the lack of a clearly validated and understood mechanical basis for this measurement of external training load, and how it relates to the mechanical stimuli that elicit internal training load. Another potentially influential factor on this relationship is the unknown degree of accuracy when assuming barbell displacement constant. Despite the need to address a number of methodological shortfalls with the VL method, its practical feasibility means it is one of the few measure of RT quantity to be viable for many coaches, sports scientists and researchers.

2.3.3. Maximum Dynamic Strength Volume Load

One of the identified limitations of the VL method is that it does not take into account the effect of body mass in the quantification of RT. This has been addressed by McBride et al. (2009) who have published the only report (to the author's knowledge) of incorporating body mass within the VL method. This measure, MDSVL, is defined as the external mass lifted summed with a proportion of body mass displaced in each repetition (McBride et al., 2009). The rationale for examining this method was that VL cannot account for RT quantity performed in exercises that do not require the displacement of any external mass (i.e. where body mass is the only mass displaced against the action of gravity). In addition to this, the conclusions of Brandon (2012) discussed in the previous section, support the inclusion of body mass with external mass for RT quantification.

When McBride et al. (2009) examined MDSVL experimentally they presented data comparing four different methods of quantifying RT. The other methods examined were VL, mechanical work and TUT. Participants performed three RT sessions using variants of the back squat exercise, one focused on each of hypertrophy (4 sets of 10 repetitions at 75 % 1RM), maximum strength (11 sets of 3 repetitions at 90 % 1RM) and power (8 sets of 6 repetitions of jump squat with no external mass). It was shown that when quantifying external training load with MDSVL there were no significant differences between the hypertrophy and strength sessions, although both were significantly greater than the power session. This led the authors to conclude that MDSVL underestimated the quantity of RT in the power session because of underestimation of the actual force production (McBride et al., 2009). The mechanical work method was concluded to be most valid as there were no significant differences between the RT quantities for the different sessions. The efficacy of the conclusions of this study have been questioned in the previous section and it is suggested the experimental design did not possess sufficient power to support them.

As discussed by McBride et al. (2009), MDSVL does demonstrate efficacy in that it is able to quantify RT performed without any external mass. Conversely, it is limited by its inability to account for TUT, velocity of movement or actual displacement. What is clear is that MDSVL is an enhancement on the VL method due to its better description of total mass displaced, shown to be a factor in acute neuromuscular responses to exercise (Brandon, 2012). Additionally, MDSVL can be easily calculated with readily available information (i.e. external mass, body mass and repetition count) making it practically feasible, as with VL. Other methods such as TUT and mechanical work utilised by McBride et al. (2009) require extensive data collection for every repetition and are practically unfeasible without considerable expenditure on equipment and labour.

The MDSVL measure is subject to the same issues as VL in that it is a measure of external training load that has not been adequately related to the mechanical stimuli of RT. It also assumes no variation in barbell or body segment displacements. Additionally, the proportion of body mass that is included in the calculation has not been determined in a robust manner. In the McBride et al. (2009) investigation, 88 % of body mass was included with external mass for the squat movement pattern based on citation of Cormie et al. (2007). This value was calculated as the percentage of body mass that the feet and shanks make up subtracted from total body mass. The rationale

was the fact that the feet and shanks are “relatively static during the phase of the lift at which peak power typically occurs” in a countermovement jump (Cormie et al., 2007, pp. 341). No data was presented to support the assertions made about the kinematics of the body segments, so the efficacy of this methodology cannot be determined.

Presently MDSVL may not be considered a theoretically robust RT quantification tool. It is a count of a proportion of body mass summed with external mass. As such, this method cannot be considered as representative of any mechanical principle more complex than a description of the displacement of mass against the action of gravity. If it is to be used to quantify external training load and establish links to internal training load, then detailed measurements must be made to determine the correct proportion of body mass to include. These measurements could only proceed after resolution of the theoretical issues with the VL measure.

2.3.4. Work

Work has been proposed as another method to quantify RT in empirical investigations (Craig and Kang, 1994, Kang et al., 1996, Cronin and Crewther, 2004, Crewther et al., 2008, McBride et al., 2009, McCaulley et al., 2009). The definition of work is a measure of the flow of energy from one body to another (Winter, 2009). Despite the relatively simple definition, the accurate calculation of work for the body-barbell system during complex multi-segmental motion is theoretically and practically difficult. Consequently, the conceptual appeal of this measure is not currently matched by its practical applicability in the everyday training of athletes.

Work has been identified as an important variable in the determination of the mechanical stimuli of RT (Crewther et al., 2005). As discussed in Section 2.3.2, work has been referred to as the mechanical underpinning for VL based on calculation of the product of barbell displacement and force (force calculated as barbell mass and acceleration due to gravity; Stone et al., 1999, Tran et al., 2006). Upon examining detailed methods of quantification of work (Winter, 2009; see section 2.5.1), this can be seen to lack accuracy. Indeed utilisation of this calculation of work for RT, as done by Craig and Kang (1994) and Kang et al. (1996), is computationally equal to change in potential energy (ΔPE). The data did show, as expected, that for a single repetition greater barbell mass led to greater work (or ΔPE) being performed (626.1 vs. 395.0 J for 3 and 25 RM, respectively; Kang et al., 1996). Conversely, the exercise protocol that

utilised the lowest barbell mass had the highest cumulative work, although this can be attributed to an increase in the number of repetitions. It should be noted there were some methodological issues with the Kang et al. (1996) study, but their data are discussed to provide broad context for the area.

Another methodological approach to calculating work during RT is deriving instantaneous force from displacement of external mass and utilised to determine work (Cronin and Crewther, 2004, Crewther et al., 2008). These investigations measured displacement with a linear position transducer and calculated velocity and acceleration as first and second derivatives, respectively. Although not explicitly described, it appears as though work has then been calculated as the cumulative of work done between each sample, measured at 200Hz. Similar results to those of Kang et al. (1996) were reported, with increases in concentric work for single repetitions with increasing barbell mass, whilst total concentric work performed in each experimental condition was better related to the number of repetitions performed (Cronin and Crewther, 2004, Crewther et al., 2008). Despite the overall pattern of findings being similar, the difference in calculation methods is demonstrated in the data of Crewther et al. (2008). There was a 30 % difference in proportion of 1RM utilised between the power and hypertrophy training conditions with only a mean difference of 44J (7.6 %) existing in the concentric work from a single repetition between these conditions. This disparity can be attributed to the lighter external mass being displaced at maximum velocity (power training) and therefore producing considerably more kinetic energy as opposed to the slower hypertrophy style training.

The methods of Cronin and Crewther (2004) and Crewther et al. (2008) are an improvement on those of Craig and Kang (1994) and Kang et al. (1996) but are still potentially prone to inaccuracy. Deriving force applied to the barbell from kinematic data is theoretically valid but is subject to possible calculation errors, especially when using the double differentiation of displacement even if filtering techniques are employed. Additionally, the method only reports the external work done on the external mass of the barbell or weight stack, negating the external and internal work performed on the body.

A third method of calculating work for RT quantification has been reported by McBride et al. (2009) and McCaulley et al. (2009). Work was measured as the area under the curve of the ground reaction force-barbell displacement graph. These data were

collected whilst participants performed repetitions of the back squat and jump squat exercises in three experimental protocols (strength vs. hypertrophy vs. power). The first of these studies concluded that quantification of RT using work was valid as no significant differences were found between the measurements made from each protocol (McBride et al., 2009). The validity of the basis of this conclusion has already been questioned in the previous sections related to VL and MDSVL. The second study demonstrated that the different training focuses in each condition elicited different acute neuromuscular and hormonal responses despite being matched for work, showing this measure is insensitive to some aspects of RT external load (McCaulley et al., 2009).

Despite the somewhat practically appealing results produced the McBride et al. (2009) and McCaulley et al. (2009), their methodology may have been flawed. The calculation procedures utilised cited an earlier investigation by one of the researchers (McCaulley et al., 2007), which in turn cited the study of Liu and colleagues (Liu et al., 2006). Importantly the subsequent studies citing the methods of Liu et al. (2006) (McCaulley et al., 2007, McBride et al., 2009, McCaulley et al., 2009) utilised barbell displacement as opposed to system centre of mass (CoM) displacement derived from ground reaction force. Combination of force and displacement data from two distinct and separate points of a system does not provide an accurate description of its kinetics or energetics (Lake et al., 2012). Therefore, the methodology of these researchers, despite the consideration of the work performed on the segments of the body, can be questioned.

Measurement of mechanical work would provide a description of external training load to quantify RT that is related to the mechanical stimuli that potentially elicit neuromuscular adaptation (Crewther et al., 2005). Unfortunately, difficulty in obtaining accurate measurements means that evidence published to date is not methodologically robust. Indeed, it presently does not seem possible to quantify this highly ecologically valid method of determining the full effect of RT in a theoretically robust manner that is also practically feasible in the training of athletes. However, the quantification of ΔPE , as inadvertently performed by Kang et al. (1996), could provide a simplified method of measuring a major component of external work performed on the barbell and warrants further investigation.

2.3.5. Time-Under-Tension

Time under tension (TUT) refers to the movement duration of an RT exercise (McBride et al., 2009). Measurement of TUT for a given exercise could include all types of muscular contraction (concentric, isometric or eccentric) or alternatively can be split into measures of each type. However, evidence from detailed studies of muscle-tendon unit interaction indicates that describing fascicle function from movement kinematics is not accurate (Fukashiro et al., 2006, Roberts and Azizi, 2010). It has been suggested that the cumulative TUT of a given training period can be used as a measure of quantity of RT performed by athletes (Tran et al., 2006, McBride et al., 2009), although it should be noted that the mass involved, displacement range and velocity of any exercise are not included.

The investigation of Tran et al. (2006) related the quantity of RT performed, as measured by TUT and VL, to acute neuromuscular responses (maximum voluntary force production and measures of neural fatigue). It was found that a reduction in TUT, whilst VL was constant, resulted in less decrease in maximum voluntary contraction (Tran et al., 2006). This, therefore, suggested that independent of VL, TUT can detect differences in the acute neuromuscular responses to RT. Conversely, rate of force development decrease was less when either TUT or VL were decreased. This shows that acute programme variable manipulations that lead to rate of force development decreases can be accounted for by either measure. The authors concluded that TUT was more sensitive than VL to detecting acute responses to RT, but that neither gave a comprehensive description and both should be considered (Tran et al., 2006).

A recently published investigation by Burd et al. (2012) compared slow and fast contraction velocities (and therefore high and low TUT, respectively) during a single bout of leg press RT. It was found that the slow RT protocol (six seconds for each of concentric and eccentric phases) elicited higher rates of mitochondrial, sarcoplasmic and myofibrillar protein synthetic rate, compared with the fast protocol (one second for each of concentric and eccentric phases; Burd et al., 2012). However, the fast contraction velocity training protocol utilised by Burd et al. (2012) is not representative of training that would be performed by athletes as it was very low intensity. These data support TUT as being a determining factor on muscular hypertrophy, although it remains for a similarly well controlled investigation remains to be performed in trained athletes.

The comprehensive review of Schoenfeld (2010) examined factors contributing to hypertrophy of muscle due to RT. Movement speed was identified as an important factor in the mechanical stimuli leading to the adaptive response, especially for eccentric muscle actions (Schoenfeld, 2010). The number of repetitions performed was also determined to be important and is a considerable factor in the cumulative TUT of a RT regime over a period of time. It was concluded by Schoenfeld (2010) that TUT in RT is related to hypertrophic adaptations, but long term this process is confounded by other factors such as magnitude of muscular tension and muscle damage. The meta-analysis of Wernbom et al. (2007) discussed the integral of the torque-time curve which is an actual measure of the mechanical stimuli of RT. However, they concluded that there was no relationship between the torque-time index and outcomes of RT across all studies examined (Wernbom et al., 2007). This method is more detailed but can only be calculated if RT is performed on an isokinetic dynamometer, limiting its practical feasibility.

Overall, TUT is a measure of external training load that is related acute and chronic responses to hypertrophy type training (Schoenfeld, 2010). However, the facts that it is not comprehensive and cannot be accurately quantified during the RT of athletes remain barriers to implementation. Therefore, TUT should be considered in the design of RT programmes and laboratory based studies but not solely relied on to describe quantity of RT.

2.3.6. Session Rating of Perceived Exertion

Session Rating of Perceived Exertion (RPE) is an index of training stress that is a modification of Borg's original scale. It requires athletes to evaluate the intensity of whole sessions of exercise, as opposed to momentary feelings of effort (Foster, 1998, Foster et al., 2001, Sweet et al., 2004). Studies have proposed the use of session RPE with continuous or intermittent aerobic exercise (Foster, 1998, Foster et al., 2001, Sweet et al., 2004), sports specific training (Foster et al., 2001) and RT (Gearhart et al., 2001, Day et al., 2004, McGuigan and Foster, 2004, Sweet et al., 2004, Singh et al., 2007, Hackett et al., 2012, Lodo et al., 2012). Implementation of this method is highly feasible with large groups of athletes and is very cost effective.

Having initially been validated in steady-state exercise modalities, the utilisation of the RPE method for RT was anecdotally widely reported (Gearhart et al., 2001). However,

this was without the validation of the relationship between RPE ratings and markers of physiological stress caused by RT, as had been established for continuous exercise (Borg et al., 1985). The active muscle RPE measure utilised by Gearhart et al. (2001) was found to be able to differentiate between high and low intensity RT protocols. This lead to the conclusion that RPE is valid for quantifying effort during RT (Gearhart et al., 2001).

Using RPE to quantify the effort of a whole session for intermittent and steady-state exercise had been examined by Foster et al. (2001). This, and the findings of Gearhart et al. (2001), led to the concept of session RPE for RT being proposed by McGuigan and Foster (2004). They also suggested that session RPE could then be multiplied by session length in minutes to calculate a value for training load that could be compared between different modalities of exercise. The same research group also published a report showing that session RPE could reliably differentiate between high, moderate and low intensity RT training (Day et al., 2004). Subsequently, Sweet et al. (2004) investigated the notion of inter-modality training quantification by comparing cycling and RT at various percentages of maximum effort. They demonstrated that the session RPE method was comparably sensitive to increases of intensity in both modalities. The data did, however, show that significant differences existed depending on whether RPE was taken for the whole session, just the time exercising or the mean of RPE taken after each set of RT (Sweet et al., 2004). Collectively these studies indicate that session RPE is able to detect global changes in intensity of RT, but that measurement issues can have a confounding effect.

The ability of session RPE to quantify RT beyond global intensity has been examined by Lodo et al. (2012). They investigated the link between subjective session RPE and quantitative measurement of RT (VL) in two different experimental protocols. The first included sets of repetitions designed to achieve three different chronic adaptations to RT whilst the second compared two relative intensities of barbell mass (Lodo et al., 2012). Significant correlations were found between session RPE scores and VL, as well as the condition with the lowest VL having the lowest session RPE. Additionally, the two different relative intensity conditions that were matched for VL did not result in different session RPE values (Lodo et al., 2012). Despite these results, the authors conclusion that session RPE was able to track changes in VL beyond their specific experimental design is questionable. The relative intensities were lower (50 and 70 % of 1RM) than previously investigated (Day et al., 2004, Sweet et al., 2004) as well as those

used for training for maximum neuromuscular force output. It could be suggested that the relationship between session RPE and VL may breakdown at higher training intensities, although this remains to be investigated.

Whilst session RPE is a good general descriptor of intensity (Day et al., 2004, Sweet et al., 2004), as well as being able to compare training between modalities (McGuigan and Foster, 2004, Sweet et al., 2004), it is not appropriate for determining external training load in relation to the mechanical stimuli of RT. It is unable to account for a number of acute programme variables that are known to impact on adaptation to RT (Singh et al., 2007) and is potentially confounded by being subjective in nature. Despite these barriers, session RPE is likely to be useful in quantifying RT to prevent overtraining where athlete perceptions of intensity could be a crucial factor (Foster, 1998). Consequently, session RPE is recommended as a valuable tool in quantifying effort in relation to RT but is outside the scope of goals of the current investigation.

2.4. Resistance Training of Elite Athletes

2.4.1. Measurements of the Back Squat

The back squat has received considerable attention in the literature, as it is one of the most popular RT exercises. It requires the athlete to start in a standing position with a barbell resting across the back of their shoulders (Figure 2.2, 1). They then flex at the hips, knees and ankles to lower the body to a predetermined depth (Figure 2.2, 2-3) and then extend through the same joints of the lower limb to return to standing (Figure 2.2, 3-5). Studies have examined how kinetic, kinematic and electromyographical variables are affected by alterations made in bar position (Gullett et al., 2009), stance width and rotation of the thigh (McCaw and Melrose, 1999, Paoli et al., 2009, Pereira et al., 2010), range of movement (Caterisano et al., 2002), and exercise intent (Pick and Becque, 2000). Knowledge of these factors can dictate acute programme variable manipulations that may in turn lead to alterations in chronic adaptations to back squat RT. Indeed, a number of studies have attempted to determine relationships between the implementation of the back squat and development of neuromuscular power (Wilson et al., 1993, Delecluse et al., 1995, Murphy and Wilson, 1997, Harris et al., 2000, Neils et al., 2005).

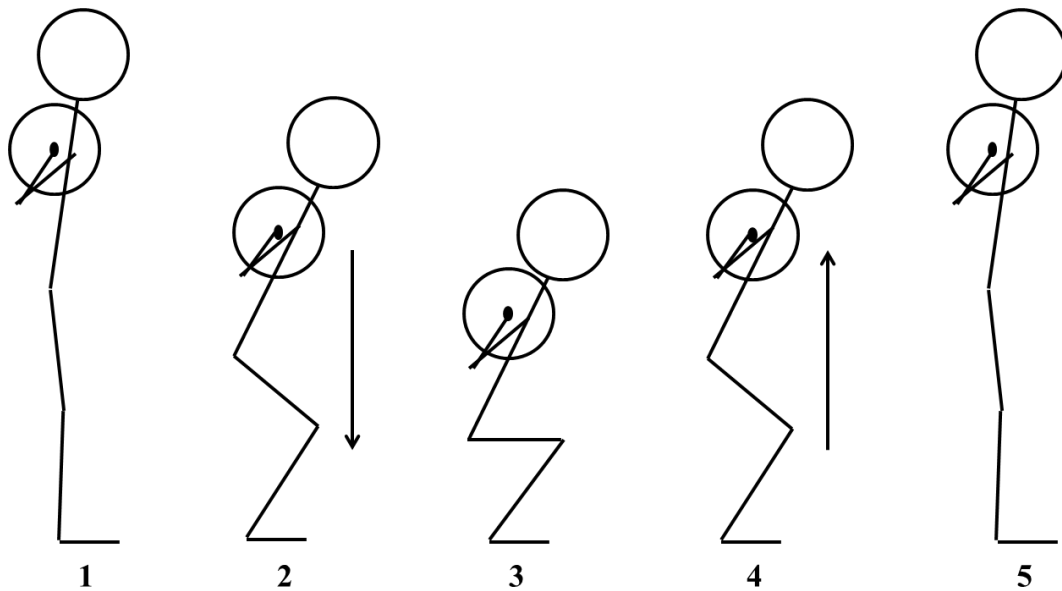


Figure 2.2. Stick figure representations of the movement sequence for the back squat. Black arrows depict direction movement in the vertical-axis at each phase.

A number of distinct variants of the back squat technique appear in the literature, with a much wider range of variations being seen in the training of athletes. Each of these can be considered a manipulation the ‘exercise selection’ acute programme variable (as defined in Section 2.2.2.). Techniques such as the traditional (also known as Olympic) squat contrast kinetically and kinematically to others such as the powerlifting and box squat varieties (Swinton et al., 2012). Selection between these is usually based on the overall training goal, with those aiming to impact on general sporting performance selecting the traditional back squat, while those aiming purely to increase back squat 1RM for powerlifting competition choose the other two varieties. The evidence for these commonly made decisions on exercise selection are based on the experiences of coaches, although in the conclusions of Swinton et al. (2012) they suggested that any of these modalities may be appropriate for athletes, depending on their physical ability and targeted neuromuscular adaptations. Other manipulations to the back squat used for training athletes include increasing gluteus maximus activation by widening traditional squat stance width (McCaw and Melrose, 1999, Paoli et al., 2009) or increasing displacement range of the barbell (Caterisano et al., 2002).

The training programmes utilised in intervention studies clearly show an ability to enhance performance in the back squat as a test of maximum strength (Murphy and Wilson, 1997, Neils et al., 2005). The RT schemes utilised have been predominantly

constructed using a range of upper and lower body exercises, representative of athletes training (Wilson et al., 1993, Delecluse et al., 1995, Harris et al., 2000), although the study of Murphy and Wilson (1997) only employed the back squat exercise to allow isolation of its effect. A common factor across these studies is poor quantification of the RT performed. Acute programme variable selection is reported (i.e. set and repetition schemes) but the external training load is not quantified in relation to the mechanical stimuli that elicit internal training load. Utilisation of experimental design similar to that of Crewther et al. (2008), is required to examine these links in determining best practice for implementing the back squat to achieve optimal neuromuscular adaptation.

As described by Garhammer (1993), due to kinetic energy being zero at the start and end of the back squat movement, the mechanical work performed on the barbell and body can be represented by ΔPE . Therefore, a key component of mechanical work, which may be an important mechanical stimuli of RT (Crewther et al., 2005), can be quantified by a relatively simple to measure variable. If data can be presented to demonstrate the validity of assuming the displacement of the barbell to be constant then a description of ΔPE could be given by VL. Additionally, utilisation of the mechanical concept of ΔPE could address the methodological issues with MDSVL, allowing ΔPE of body mass to be incorporated with that of the barbell.

The back squat is highly prevalent in RT focused on achieving increases in maximum neuromuscular force and power output, as well as muscle hypertrophy. However, due to a lack of research with consistent training quantification methods, the chronic effect of many common acute programme variable manipulations is unknown. Use of ΔPE to quantify external training load in relation to the mechanical stimuli of RT performed with this exercise would allow comparison of experimental doses to help optimise the training of athletes whilst preventing the negative effects of inadequate recovery.

2.4.2. Measurements of Olympic Weightlifting and Derivative Exercises

The Olympic weightlifting exercises (clean and jerk, and snatch) require high neuromuscular force output to displace the barbell within a short time frame, leading to high power outputs (Garhammer, 1980). Each of the two lifts has different technical specifications but both broadly rely on the rapid and forceful extension of the hips, knees and ankles (termed triple extension).

Published research focusing on Olympic weightlifting exercises began to expand towards the end of the 1970s with numerous publications focusing on determining the power output of elite lifters (e.g. Enoka, 1979, Garhammer, 1979, 1980, 1982, 1985, 1991). As much of this data was collected in competition, all variables were calculated from data obtained by 2-dimensional digitisation of sagittal plane video images. Despite some potential measurement inaccuracy, these studies provided previously unavailable information to describe and develop performance within the sport of weightlifting. Due to the high power outputs measured during these exercises (~7000W; Garhammer, 1993) their relevance for increasing power output in athletes from other sports became more apparent. Consequently, the Olympic weightlifting exercises and their derivatives have increased in popularity in the training of athletes outside of the sport of weightlifting (Kilduff et al., 2007, Comfort et al., 2011a).

Derivative exercises based on Olympic weightlifting typically break down the full movements into their constituent phases to emphasise particular elements. These exercises are used in the training of competitive weightlifters but are also useful for other athletes who may be technically limited in their compete execution. One example is the power clean that does not require the lifter to dip into a full front squat position to catch the bar, and can be started with the barbell either resting on the floor or from a hanging position just above the knee or mid-thigh (Comfort et al., 2011a, Comfort et al., 2011b). The second pull is typically the portion of the clean exercise that is focused upon, because it has been shown to be when the greatest vertical ground reaction force is generated (Enoka, 1988) and also its hypothesised similarity to sporting performance. One of the most commonly utilised derivative exercises is the hang clean and it is depicted in Figure 2.3. From a start position, holding a barbell just above the knee (Figure 2.3, 1), the athlete is required to explosively extend the legs to displace the barbell vertically as rapidly as possible (Figure 2.3, 2-4), before dipping slightly to catch it on the anterior portion of the shoulder (Figure 2.3 5-6). The popularity of the hang clean in training athletes is fuelled by evidence showing ability to perform this exercise is related to sports specific performance tests such as sprinting and jumping (Hori et al., 2008). However, this evidence is not conclusive and best practice in prescription of training to develop these physical abilities remains to be determined.

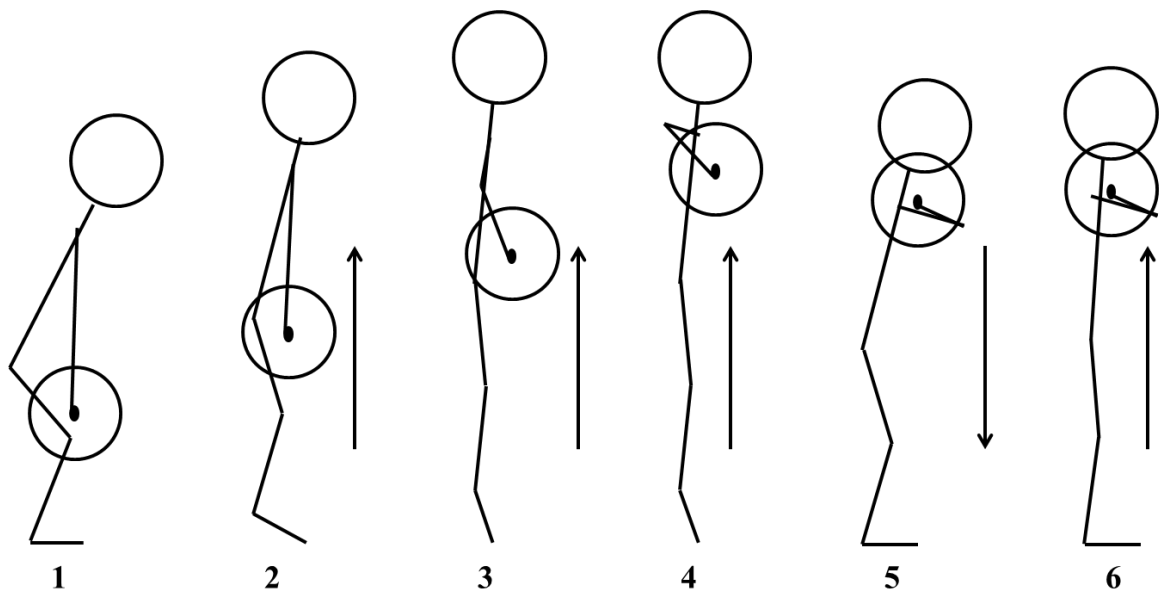


Figure 2.3. Stick figure representations of the movement sequence for the hang clean. Black arrows depict direction movement in the vertical-axis at each phase.

The increase in detail and measurement accuracy of laboratory based investigations into Olympic style resistance training exercises have improved available information on the impact of manipulations of acute programme variables. A number of investigations have attempted to determine the relative barbell mass at which peak power production occurs (Kawamori et al., 2005, Cormie et al., 2007, Kilduff et al., 2007). The results of these three studies suggested that 70-80 % of 1RM barbell mass elicited the greatest peak power production, although this was not confirmed statistically. These investigations utilised an ‘above knee’ hang clean exercise. To establish the kinetic difference between this and other techniques, Comfort et al. (2011a) examined vertical ground reaction force and rate of force development between three exercise variations. They showed that the mid-thigh start position for a power clean produced the greatest peak force and rate of force development and concluded this exercise could be best for developing these qualities.

As with the back squat, research has examined in detail the acute kinematic and kinetic effects of manipulations in acute programme variables, as well as examining chronic adaptations when training with Olympic style weightlifting exercises. The emphasis on barbell velocity, resulting in high power outputs, means that the mechanical stimuli contributing to internal training load are considerably more complex than the back squat. Some of the studies examining chronic adaptations have utilised VL to quantify RT (Fry et al., 1994, Fry et al., 2000, Haff et al., 2005, Haff et al., 2008) which does not account

for these velocity related components. However, data from Garhammer (1993) indicate that a large proportion (77 % entire lift; 92 % second pull) of total mechanical work done during a clean is accounted for by ΔPE of the barbell. Additionally, Garhammer (1993) highlighted that the ΔPE of the segments of the body makes a substantial contribution to the total power of a lift (16% of total power for whole lift and second pull). Therefore, the proposed use of VL to provide a representation of ΔPE of the barbell and body may provide a means to quantify external training load in Olympic style weightlifting exercises that is related to the mechanical stimuli for adaptation.

2.4.3. Variability in Resistance Training Technique

Previous sections have established that ΔPE could be utilised as a quantitative measure of RT that is related to the mechanical stimuli for adaptation, as well as allowing scope for incorporation of the displacement of body mass. However, using ΔPE as the underpinning would be based on the assumption that barbell and body displacement are constant between repetitions. This assumption has been made by other authors (Stone et al., 1999, Tran et al., 2006), but has not been examined experimentally in this context. Displacement cannot be exactly the same for every repetition over time. Therefore, the level of accuracy of the assumption is related to the magnitude of variation in this variable. Following the terminology of Atkinson and Nevill (1998), differences between repetitions can be described as random error of displacement due to biological or mechanical variation. This will be referred to as variation for the purposes of this thesis.

Despite the lack of evidence relating to variation of barbell displacement in the context of quantification of RT, there are some data that can inform the discussion. The effects of repetition scheme on fatigue when performing power cleans was examined by Hardee et al. (2013). It was shown that when performing three sets of six consecutive repetitions, there was a decrease in barbell displacement within each set (Hardee et al., 2013). The authors concluded that repetition schemes allowing rest between each lift attenuated of the negative impacts of fatigue on kinematic and kinetic factors associated with technique. Whilst employing a different experimental design, and examining the bench press, Duffey and Challis (2007) found that in performing a set to failure at 75 % of 1RM caused significant changes in barbell kinematics. Displacement magnitude was not affected as the range of the bench press is set by anatomical constraints, but barbell velocity and exercise execution strategy were considerably different between the first and last repetition (Duffey and Challis, 2007). Both of these studies did not directly

quantify variation but showed that the fatigue effects of consecutive repetitions can impact on barbell displacement and so should be considered when assessing the variation of RT. One study has been conducted that has determined the variation of a number of kinetic variables during repetitions of the front squat exercise (Caruso et al., 2012). Unfortunately displacement was not discussed in this article, although the authors concluded that the biological variation they observed (10-15 % coefficient of variation [CV] for majority of variables) was of an acceptable limit.

The investigations of Duffey and Challis (2007) and Hardee et al. (2013) discussed variation of the outcome of each exercise, but also that of the process by which the outcome was achieved. It is between these two sources of variation that a clear distinction should be drawn. This topic is discussed in detail by Bartlett et al. (2007), who highlighted the strengthening evidence base within the biomechanical motor control literature that movement pattern variation contributes to successful outcomes. It was suggested that variation in human sporting movement patterns is not 'noise' as previously thought, but the result of the complex motor control strategies (Bartlett et al., 2007). Whilst the research in this area is far from comprehensive, none of the evidence reviewed by Bartlett et al. (2007) refuted this hypothesis. Barbell displacement is considered the outcome of RT exercises in the present investigation and is therefore analogous with the performance (e.g. distance thrown) discussed by Bartlett et al. (2007). Examination of the factors contributing to the bio-motor control that achieves these outcomes is outside the scope of this investigation.

Some studies have quantified the variation of performance variables and descriptors, although they do not directly relate to RT. These data are of interest, however, as they can provide a background against which the variation in RT exercises can be compared. When examining a number of jump assessments, Markovic et al. (2004) found that CV ranged from 2.4 to 4.6 %, with all of these being deemed acceptable. Similarly, Sattler et al. (2012) studied the variation of standard and volleyball specific jumping tests. They found CV values ranging from 2.1 to 2.8 % and also concluded that this demonstrated low variation (Sattler et al., 2012). Outside of performance tests, Salo and Grimshaw (1998) examined the variation of a number of sprint hurdle technique variables and described CV values ranging from 1.0 to 209.7 %. Despite this range, for females and males 15 and 14 variables out of 28, respectively, fell under a 5 % limit.

Across the sports science and medicine literature, CV values of less than 5 % are frequently described as representing low variability. Whilst these conclusions appear intuitive, the level of variation as calculated by this statistic should always be carefully interpreted in the situational context. This is due to the various considerations that are associated with its use, meaning comparing it to analytical goals is problematic and potentially invalid (Atkinson and Nevill, 1998). Despite this necessary caution, CV is a useful descriptor of variation that provides values comparative to the original units of measurement for a variable.

Variability is a key concept for any investigation into movement technique, but is particularly important if assumptions are to be made about a given variable's magnitude or deviation from mean value. All movement will display a degree of variation in process and outcome, and thus will never be totally reproducible. However, if practically applicable RT quantification tools are to be developed, knowledge of the magnitude of technique variation is vital. This will allow a degree of accuracy to be assigned to measures employed in intervention studies and inform the development of relationships between external training load and subsequent responses.

2.5. Calculation and Measurement Issues

2.5.1. Quantifying Change in Potential Energy

It has been established in Sections 2.3 and 2.4 that displacement of mass against the action of gravity is a key aspect of RT, potentially leading to the mechanical stimuli that result in neuromuscular adaptation. Consequently, representation of ΔPE is a possible method of quantifying external training load in empirical investigations and the training of athletes. The study of biomechanical energetics encompasses the interaction between work, energy and power, and can provide considerable information about human movement (Winter, 2009). If one of these variables is to be measured, then of its interaction with the others must be considered. However, when used in the context of RT quantification, these terms are often not defined or are used together without delineation. Energy and work are clearly defined by Winter (2009): energy is the ability of a body to do work at a given instant in time, whilst work is the flow of energy from one body to another over time. The energy of a body at a point in time can be described as the sum of its potential and kinetic energies.

In RT, as with any human movement, mechanical energy can only be produced by sarcomeres. Mechanical energy leads to positive or negative muscle work being performed in situations that do not involve isometric contractions. Energy can be transferred from where it is produced, to one or more segments of the body via passive and active structures thus doing work elsewhere in the system. The work that is performed on the segments of the body relative to its CoM is termed internal work, whilst work performed on the body's CoM or external bodies is termed external work. Therefore, in a given RT exercise with an external load, mechanical energy produced by sarcomeres results in internal and external work, leading to energy change of the segments of the body and external load. For example, when performing a back squat, the hip and knee extensors produce the majority of the work, but this has to be transferred to the barbell via the torso, resulting in potential and kinetic energy changes.

Despite the majority of RT techniques eliciting their effects via displacement of mass against the action gravity, there is very little research discussing the influence of ΔPE on adaptation of the neuromuscular system. The work of Garhammer (1982, 1993) demonstrated that valuable performance and training information can be determined by relatively simple analysis. Indeed, as discussed previously, data from Garhammer (1993) indicate that a large proportion of total mechanical work done during a clean is accounted for by ΔPE of the barbell. Additionally, Garhammer (1993) also highlighted that the ΔPE of the segments of the body makes a substantial contribution to the total power of a lift. Therefore, despite the complex nature of the determinants of successful execution of Olympic weightlifting exercises, a large part of the performance can be described as displacing mass against gravity. With exercises such as those used in Olympic weightlifting being well described by ΔPE , it is logical to propose that other exercises involving simpler movement patterns and without the emphasis on barbell velocity (e.g. the back squat) could also be well described by this mechanical concept.

Quantifying mechanical work during human movements has received considerable attention in the literature with the primary focus being on locomotion (Quanbury et al., 1975, Winter, 1979, Willems et al., 1995, Purkiss and Robertson, 2003, Sasaki et al., 2009). These studies have been concerned with quantifying the energy cost, energy flow or the efficiency of various styles of gait. Two predominant methods have been utilised to estimate muscle mechanical work, and either quantify work done via segment kinematics or by integration of joint power calculated through inverse dynamics procedures (Sasaki et al., 2009, Winter, 2009). Measurement and theoretical issues exist

with each of these methods, meaning there is no gold standard for measurement of mechanical energy and work during human movement.

Despite ΔPE not being a comprehensive description of mechanical work during RT, it is the predominant factor in overall change in energy levels during many exercises (Garhammer, 1993). Combined with the possibility of using this mechanical concept as the basis of a practically feasible RT quantification method, further examination of ΔPE in RT is warranted. Measurement of this single aspect of the energetics of human movement requires considerably less complex methods compared with more comprehensive internal and external work analysis (Willems et al., 1995, Sasaki et al., 2009). This has been demonstrated previously in the methods of Garhammer (1982, 1993) although there was some inaccuracy associated with these measurements. Utilisation of modern kinematic measurement systems can reduce the error of resulting calculations of a segment-by-segment approach to determining ΔPE .

2.5.2. Variability and Reliability Statistics in Sport and Exercise Sciences

Variability is an important concept in sport and exercise sciences, especially when conclusions or assumptions about a given variables magnitude or deviation from the mean are being drawn from data (Section 2.4.3). It is often described as being a component of the wider area of reliability. Atkinson and Nevill (1998) and Hopkins (2000) referred to reliability as being the reproducibility or consistency of a measurement or test. This was clarified in practical terms as being “the amount of measurement error that is deemed acceptable for effective practical use of a measurement tool” (Atkinson and Nevill, 1998; pp.219). Generally, reliability encompasses measurement accuracy, systematic bias in a test and random error due to biological variation. It is clearly distinguished from validity, which refers to whether a test measures what it is intended to. Reliability can be also considered as relative or absolute depending on whether scores for a test are interpreted as rank within the group or as the magnitude of an individual’s score.

Due to the different components of reliability, many different statistical methods can be employed in its quantification. These include comparisons of means (t-test and analysis of variance [ANOVA]) to determine systematic bias and correlational techniques (Pearson’s r) to determine rank within a group or absolute measures (CV and standard error of measurement) that describe reliability of specific tests for individuals (Atkinson

and Nevill, 1998, Hopkins, 2000). A central theoretical issue surrounding the assessment of reliability is whether a measure can be significantly reliable. It has been discussed by Morrow and Jackson (1993), and they clearly stated that reliability should not be assessed as to whether it is statistically significant. Rather measures of reliability should be clearly reported and it be left to the reader to determine practical significance based on the available evidence (Morrow and Jackson, 1993).

In determining the efficacy of assumptions made for quantitative measures of RT, two components of reliability are of particular interest with these being variability and systematic bias. Common statistical tests for assessment of these issues are CV and ANOVA. The CV statistic is a representation of the standard deviation (SD) of a number of measurements as a percentage of the mean (Atkinson and Nevill, 1998, Hopkins, 2000). As defined, the terms variation or variability refer to random error from biological or mechanical sources. Consequently, CV could contribute to determination of the degree of error created by assuming a given variable constant, although measurement error and systematic bias need to be accounted for in experimental design.

One of the key issues with using CV in studies of variability is the difficulty in defining practical meaning when examining a particular analytical goal (Atkinson and Nevill, 1998). As highlighted by Atkinson and Nevill (1998) assigning an arbitrary CV threshold for acceptable variability is not sufficient to formulate conclusions from. With CV being influenced by the magnitude of the sample mean, a CV value that may represent low variability for one variable may represent high variability for another. Examination of studies using CV reveals that values of 0-5 % are consistently described as representing low variability (Jeukendrup et al., 1996, Hopkins et al., 2001, Austin et al., 2013, Kwah et al., 2013, Lockie et al., 2013) although each of these conclusions are only relevant to the specific context of the data presented. Other issues with CV include the requirement of normality of data for use of the parametric methods of mean and SD as well as heteroscedasticity.

Use of the ANOVA procedures allows for systematic bias in mean values between two or more groups of measurements to be assessed for statistical significance. The limitation of using ANOVA procedures in studies of reliability is that high random error within the data set could lead to acceptance of the null hypothesis and consequently false conclusions of no systematic bias (Atkinson and Nevill, 1998). Consequently, ANOVA procedures cannot be used in isolation to determine reliability or variability

but can be interpreted in conjunction with absolute measures, such as CV. Albery et al. (2006) directly used the two procedures together by determining systematic bias in CV values using an ANOVA procedure.

All repeated measures ANOVA procedures are subject to the assumption of sphericity. This assumption can be examined using Mauchly's test and if significant asphericity is revealed then either the Greenhouse-Geisser or Huynh-Feldt corrections can be applied. The recommendations of Girden (1992) and Atkinson (2001) state that if significant asphericity is detected then the Greenhouse-Geisser adjusted p-value should be used if its epsilon value is > 0.75 . If this is not the case the Huynh-Feldt adjusted p-value should be used. When multiple comparisons are made using ANOVA procedures and a statistically significant p-value is returned, it remains to be established for which of the multiple comparisons the significant difference exists. This can be determined by making specific comparisons, for example, with a Ryan-Holm-Bonferroni adjustment (Ryan, 1960, Holm, 1979). This procedure reduces the chance of type I errors associated with the Bonferroni technique whilst maintaining its statistical power (Atkinson, 2002). This balance between power and probability of error ensures systematic differences in mean are detected.

The commonly used Pearson's correlation coefficient is inappropriate in many contexts for assessing reliability as it does not account for the magnitude of variables (Atkinson and Nevill, 1998) and can be confounded by variability of the data (Bates et al., 1996). The intra-class correlation coefficient (ICC) provides a valid method for evaluating the reliability of data sets that share measurement units and variance (McGraw and Wong, 1996). The work of McGraw and Wong (1996) discussed the differences between different types of ICC and considerations for their selection. These included the type of model (one or two way), whether data represent random or mixed effects, if average or single measures are analysed and if absolute or relative reliability is assessed. Each of these issues result in modifications to the reliability model used and consequently calculation methods employed (McGraw and Wong, 1996). Lack of consideration of these factors has been identified as a common error in reliability study design (Morrow and Jackson, 1993).

2.6 Literature Review Summary

Quantification of RT in athletic populations and empirical investigations is a highly relevant issue in the context of research into enhancing sporting performance. The accuracy of the most prominent method to date, VL, has not been assessed, nor has detailed description been provided of how it is related to the process of neuromuscular adaptation. Considering the need for scientific validity, combined with practical applicability in measures of RT quantity, ΔPE appears the most feasible mechanical basis for a quantitative metric that will provide this balance. However, for this to be possible, the accuracy of unverified assumptions about kinematic quantities of movement need to be determined, and the associated error interpreted within the context in which they will be applied.

CHAPTER 3: METHODOLOGY

3.1. Participants

To address the established research questions ten male professional strength and conditioning coaches were recruited to complete the experimental protocol (individual descriptive information is in Table 3.1). Ethical approval was granted by the University of Bath Department for Health ethics committee and informed written consent was obtained prior to data collection. All participants were accredited with the United Kingdom Strength and Conditioning Association and had a minimum of two years' experience performing the back squat and hang clean to the required technical standard. However, two participants did not attempt the hang clean, one due to a wrist injury and the other due to a lack of recent training history in this exercise.

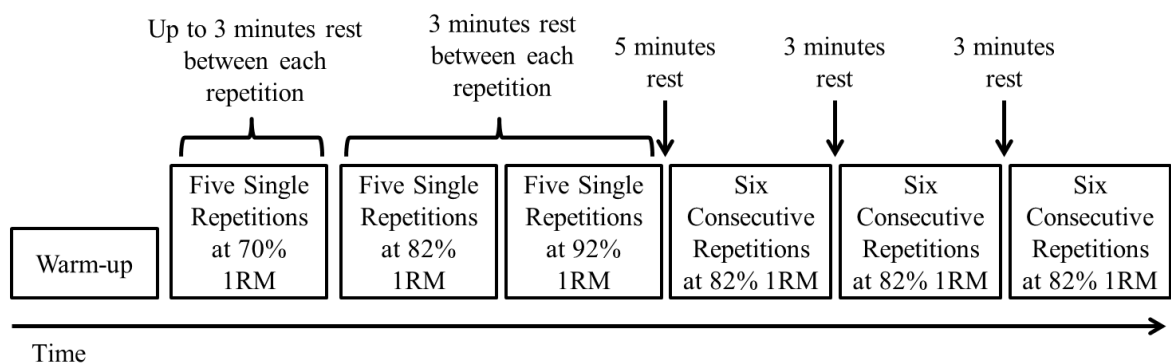
Table 3.1. Individual participant information. 1RM values were self-reported.

Participant	Height (m)	Body Mass (kg)	Back Squat 1RM (kg)	Hang Clean 1RM (kg)
P1	1.775	85.4	160	100
P2	1.829	86.8	150	75
P3	1.799	89.1	145	85
P4	1.840	99.2	210	130
P5	1.682	70.5	115	70
P6	1.745	80.8	125	85
P7	1.808	83.2	107.5	
P8	1.673	88.7	187.5	
P9	1.800	94.7	150	72.5
P10	1.902	102.8	150	125
Group	1.785 ± 0.070	88.1 ± 9.3	150.0 ± 31.2	92.8 ± 23.4

3.2. Data Collection

A cross-sectional design was utilised for this investigation. On different days, separated by at least 72 hours, participants performed 33 repetitions of either the back squat or hang clean. At the start of the testing session, participants performed a warm-up

comprised of self myofascial massage (hip, upper leg, lumbar and thoracic spine; ~5-10 minutes), dynamic mobility exercises (deep squat and lunge groin mobilisations; ~5 minutes), body weight triple extension activation exercises (squat, reverse lunge, countermovement jump; 1-2 sets of 8-12 repetitions) and repetitions of the experimental exercise (incrementing mass; 1-2 sets of 4-6 repetitions at unloaded, ~30 and ~60 % of 1RM). The 33 repetitions were split into two groups, single repetitions (15 repetitions) and sets of consecutive repetitions (18 repetitions), and each of these had three sub conditions (Figure 3.1). The single repetitions were split in three groups of five, with barbell masses of 70, 82 and 92 % of 1RM, respectively. The rest period for repetitions at 70 % of 1RM was between 1.5 and 3 minutes (at participant's discretion) and was strictly 3 minutes between repetitions at 82 and 92 % of 1RM. These three conditions allowed the effect of increases in barbell mass on barbell and body Δ PE parameters to be determined. The relative masses represented ~ 12RM, ~ 6RM and ~ 3RM and are considered light, moderate and heavy training loads for the selected exercises (Kraemer and Ratamess, 2004). The different relative barbell mass conditions were termed BS70, BS82 and BS92 and HC70, HC82 and HC92 for each exercise, respectively. The conditions were performed in ascending barbell mass order as this is the structure of a typical training session for athletes. Following a period of 5 minutes rest, the participants then performed three sets of six consecutive repetitions at 82 % of 1RM with three minutes rest between sets (time from end of one set to beginning of next).



The sets of consecutive repetitions allowed the effect of multiple repetitions without rest on barbell and body Δ PE parameters to be determined. These conditions were termed BSS1, BSS2 and BSS3 and HCS1, HCS2 and HCS3 for each exercise, respectively.

Figure 3.1. Schematic representation of the repetition structure for each data collection session.

A 20 kg Eleiko Olympic Weightlifting training bar (Eleiko Sport AB, Halmstad, Sweden) was used for all testing sessions. The required percentages of individual 1RM barbell mass for each test condition were made up with a combination of 25, 20, 15, 10, 5, 2.5 and 1.25 kg Eleiko weight plates. This gave a minimum resolution in barbell mass of 2.5 kg, and thus if the required barbell mass could not be achieved exactly it was rounded to the nearest 2.5 kg. Actual mass lifted for the back squat corresponded to $70.4 \pm 0.7 \%$; $82.0 \pm 0.5 \%$; $91.9 \pm 0.5 \%$ of 1RM for BS70, BS82 and BS92, respectively, and for hang clean $70.1 \pm 0.8 \%$; $81.9 \pm 1.0 \%$; $92.3 \pm 0.8 \%$ of 1RM for HC70, HC82 and HC92, respectively.

Kinematic data was collected at 200Hz using the CODA Motion CX1 system (Charnwood Dynamics, Leicestershire, UK; static resolution in the antero-posterior and vertical-axes of 0.05 mm and medio-lateral axis 0.3 mm) for all repetitions. A schematic representation of equipment set-up is available in Figure 3.2. Active infrared markers were affixed on the skin of the following anatomical landmarks: 2nd metatarsophalangeal joint, lateral malleolus, lateral epicondyle of the tibia, greater trochanter, sternoclavicular notch, tragus of the pinna (representative of the ear canal), acromion, the most proximal point on the lateral edge of the radius, styloid process and 3rd metacarpophalangeal joint (de Leva, 1996a, Winter, 2009). Markers and their associated battery packs were secured using double sided and micropore tape. Five markers were affixed to the barbell to allow measurement of two points on the centre of rotation (CoR) of the barbell in the medio-lateral axis which were both a known distance from the barbell's CoM (Figure 3.3).

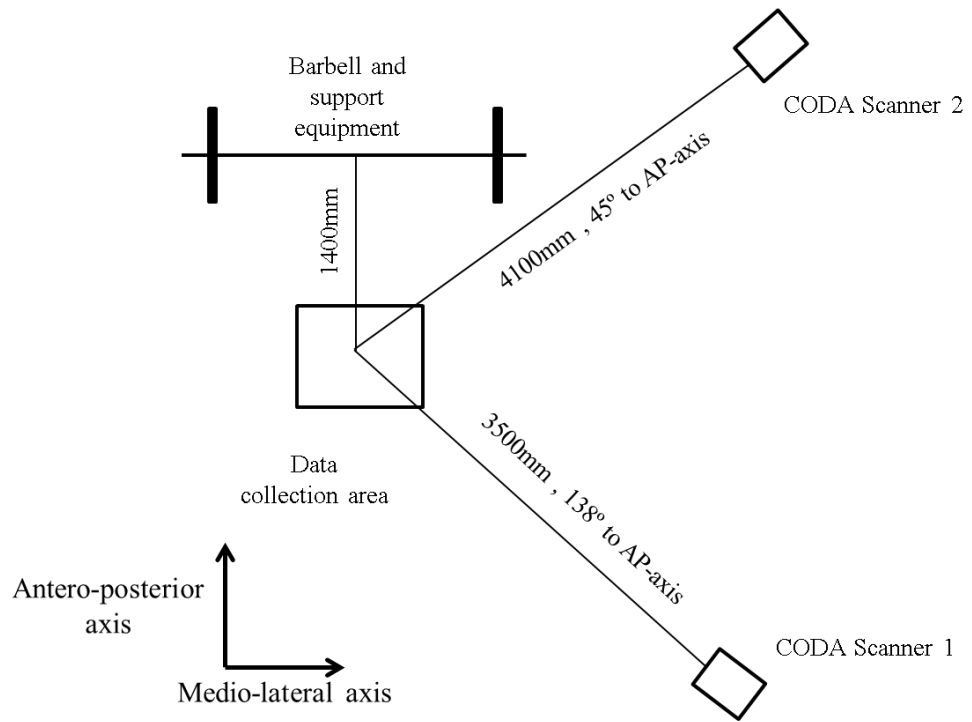


Figure 3.2. Schematic representation of the experimental set-up in the transverse view.

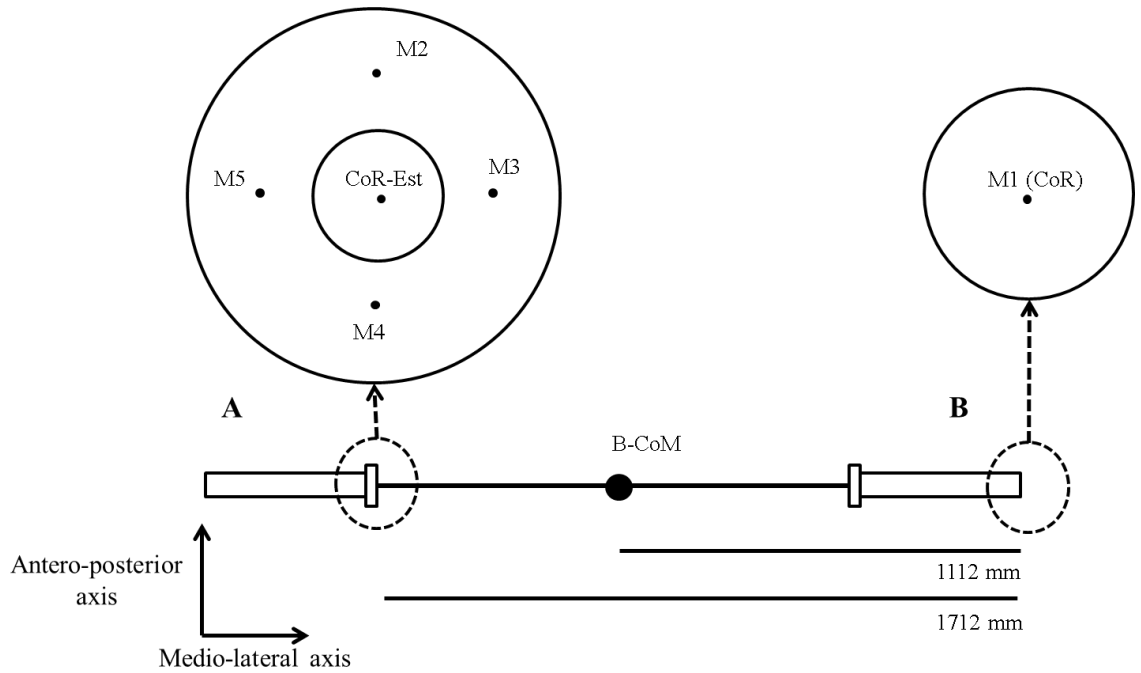


Figure 3.3. Transverse view of unloaded barbell with sections shown in the sagittal plane of the sleeve end (A) and barbell end (B) to demonstrate marker positions. M1 represents the CoR of the barbell at the barbell end, CoR-Est is the estimated CoR of the barbell at the sleeve end (from M2-M5) and B-CoM is the barbell CoM location.

The technique definition of the back squat was as follows (bracketed numbers refer to positions in Figure 2.2): from standing upright with feet flat on the ground (1), flex hip,

knee and ankle (2) to achieve a mid-point position where the top inguinal fold is below the top of the patella (3) and then extending the hips, knees and ankles (4) to return to standing (5) whilst not increasing the torso angle relative to the positive vertical axis. The start position of the hang clean was defined as (bracketed numbers refer to positions in Figure 2.3): feet flat on the ground, partially flex the knee and hip to allow the barbell to be lowered to just above the patella with the shoulder joint displaced slightly anterior of the vertical line through the barbell (1). To perform the repetition the hips, knees and ankles are explosively extended to displace the barbell vertically (2-4) before being caught on the anterior portion of the shoulders in a partially squatted position (5), before finally extending the legs to a standing position (6; Kilduff et al., 2007). Weightlifting straps were permitted to be used for the hang clean, if required, and all participants wore their normal footwear for RT sessions.

The barbell was supported between repetitions with either portable squat stands (back squat) or weightlifting blocks (hang clean). This was for the safety of the participants, and in the case of the hang clean, to eliminate the fatigue encountered from picking the barbell up from the floor for each repetition. Due to the measurement system used, the support equipment had to be placed further forward from the exercise execution position than would be normal for participant's everyday training purposes. This was necessary to prevent the CODA markers being occluded by this equipment during the exercise movement phases. At the start of each repetition, the participants picked up the barbell from the support equipment and stepped backwards to the exercise execution position. As soon as they were in a stationary, upright standing position, the data collection was started and a verbal prompt given to begin the movement. A data collection period of ten seconds was allowed for each single repetition trial. For the sets of consecutive repetitions, 60 seconds was allowed, although no participants used all of this time. Participants were asked to pause for at least one second at the end of a repetition to allow the end point of the movement to be easily identified in the analysis. For the single repetitions, once this pause was over, they could return the barbell to the support equipment.

All participants were aware that the purpose of the study was to examine variability in barbell lifting technique. They were requested to perform all repetitions in a controlled and consistent manner at the beginning of the session. Verbal feedback was given during the warm-up repetitions to ensure their movement pattern met the criteria previously defined. Once the data collection had commenced no further feedback on

their technique was given. This was to ensure the data gave an accurate representation of the participant's ability to reproduce the movement pattern of the exercises.

3.3. Data Processing

The kinematic data was filtered at 100Hz to remove high frequency noise and then used to create an eight segment unilateral model of the body: foot, shank, thigh, torso, head, upper arm, lower arm and hand (de Leva, 1996a, Winter, 2009). All calculations were performed using Microsoft Excel 2010 (Microsoft Corporation, Redmond, USA). The 3-dimensional marker position coordinates and marker visibility data were exported from CODA Motion Analysis (Charnwood Dynamics, Leicestershire, UK) as text files and then imported to Microsoft Excel. For the body, the marker coordinates were considered representative of joint centre position, with the exception of the acromion marker. This was due to the discrepancy between acromion marker position and shoulder joint centre. The vertical marker offset values provided by de Leva (1996b) were utilised to calculate an estimate of shoulder joint centre position. When the trunk was not vertically inclined (zero degrees relative to the vertical axis) this value had to be adjusted to account for the translation of joint centre in the antero-posterior axis. This was performed using trigonometric functions with the calculated angle of the trunk relative to the vertical axis. For a given segment, the vertical coordinate of its CoM (Z_{S-CoM}) was calculated as a percentage of the distance from distal (Z_{dist}) to proximal (Z_{prox}) vertical coordinates as shown in de Leva (1996a). The head CoM vertical coordinate was assumed to be represented by the vertical coordinate of the marker on the tragus of the pinna due to logistical issues with capturing the kinematic motion of the head.

The barbell CoM vertical coordinate (Z_{B-CoM}) was calculated as a proportion of the distance between two points on the CoR of the barbell in the medio-lateral axis (vertical coordinates of marker M1 [Z_{M1}] and the estimated CoR at the sleeve end [$Z_{CoR-Est}$]; Figure 3.3). Due to marker occlusion from the rotation of the barbell, $Z_{CoR-Est}$ had to be determined from any of the six combinations of two visible markers from the four available (M2-5; Figure 3.3). If more than one combination was visible then the mean of the $Z_{CoR-Est}$ values was taken. For the two combinations of opposite markers, $Z_{CoR-Est}$ was calculated as the mean of their vertical coordinates. The remaining four combinations consisted of two adjacent markers that formed a right-angled isosceles triangle with $Z_{CoR-Est}$ as the vertex. As distances between each marker and the centre of

rotation of the barbell were known, $Z_{\text{CoR-Est}}$ could be calculated from the vertical coordinates of any of the combinations of M2-M5.

The back squat was split into downward and upward phases, determined by change in $Z_{\text{B-CoM}}$. The downward phase was denoted by the first time point where change in $Z_{\text{B-CoM}}$ became negative and remained so (mark 1, Figure 3.4 A). Small fluctuations in the trajectory of displacement of the barbell ($<10\text{mm}$ or <3 samples) were ignored as these were attributed to biological variation, noise within the CODA system or the calculation method of $Z_{\text{B-CoM}}$. The end of the downward phase, and consequently beginning of the upward phase, was the first sample where change in $Z_{\text{B-CoM}}$ became positive and remained so (mark 2, Figure 3.4 A). The end point of the upward phase was the first sample that change in $Z_{\text{B-CoM}}$ became negative and remained so (mark 3, Figure 3.4 A). For the back squat, ΔPE was analysed during the upward phase.

The hang clean was split into the 1st upward phase, downward phase, 2nd upward phase and standing phase. The beginning of the upward phase was denoted by onset of positive change in $Z_{\text{B-CoM}}$ from the 'set' position (marker 1, Figure 3.4 B). The end of the upward phase was the point of first negative change in $Z_{\text{B-CoM}}$ (marker 2, Figure 3.4 B). The downward phase began at the end of the upward phase and ended at the point of local minimum $Z_{\text{B-CoM}}$ (marker 3, Figure 3.4 B) prior to the maximum $Z_{\text{B-CoM}}$ for the entire trial. The 2nd upward phase started at the end of the downward phase and ended at the point of maximum $Z_{\text{B-CoM}}$ (marker 4, Figure 3.4 B). Finally, the standing phase was a period of minimal change ($<30\text{ mm}$; determined from values obtained in pilot testing) in $Z_{\text{B-CoM}}$ subsequent to the 2nd upward phase, where the participant was standing with the barbell resting on the anterior portion of their shoulders (markers 5-6, Figure 3.4 B).

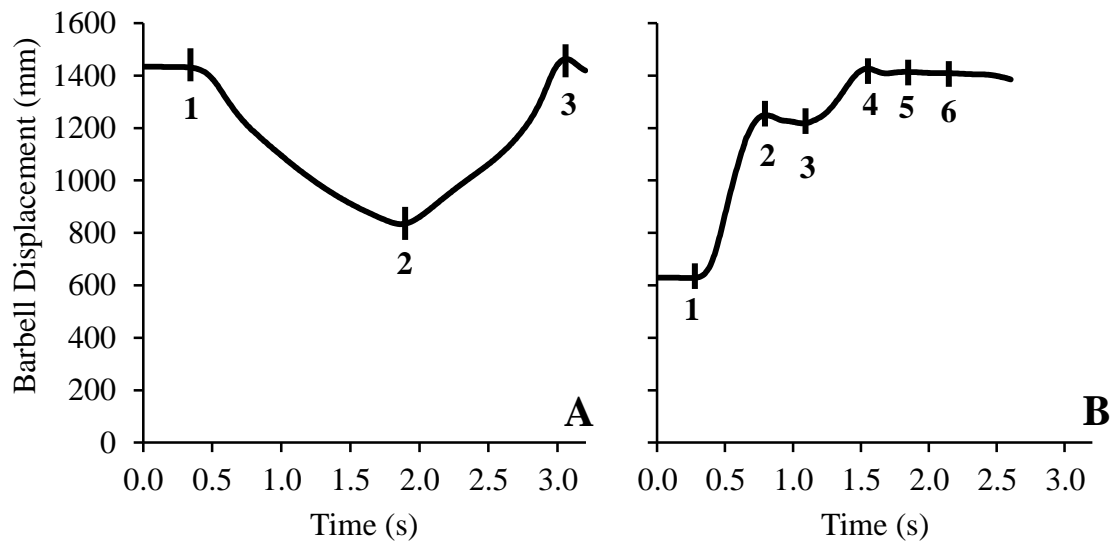


Figure 3.4. Exercise phase definitions based on barbell displacement for the back squat (A) and hang clean (B).

The 1st upward phase of the hang clean is intended to mimic the portion of the full clean where peak power output occurs (Enoka, 1988) and therefore creates the overload to elicit neuromuscular adaptation. Studies investigating the force-time characteristics of Olympic weightlifters performing the clean have either analysed data to peak barbell velocity or displacement, and not considered the downward or 2nd upward phases (Enoka, 1979, 1988, Garhammer, 1980, 1982, 1985, 1988). Indeed, Garhammer (1993) described the clean and front squat as distinct elements of the full clean, suggesting the movement phase up to peak barbell displacement should be considered separately to subsequent phases. The difference is due to the relative intensity, velocity and intent of the 2nd upward phase being considerably lower to that of the 1st upward phase in the hang clean. Kinematically the 2nd upward phase is similar to a partial front squat and Hartmann et al. (2012) showed that partial back squat 1RM is considerably greater than full or parallel squat 1RM (partial back squat 1RM 144 % greater than deep back squat 1RM). Therefore, considering the parallel back squat 1RM values of the participants in the present study (150.0 ± 31.2 kg), the hang clean barbell masses (92.8 ± 23.4 kg) can be considered to be low relative intensity (<50 %) for a partial front squat.

The primary Δ PE analysis for the hang clean was performed during only the 1st upward phase based on the clear distinction in movement intensity and intent compared with the subsequent phases. This conclusion was supported by the clear disassociation of barbell displacement-knee angle relationship between the different phases of the hang clean (Figure 3.5). However, despite kinematic and kinetic differences, data will also be

presented for the barbell during the downward and 2nd upward phases as they cannot be concluded to be insignificant. Potential energy data for the body cannot be calculated beyond the end of the 1st upward phase due to marker occlusion.

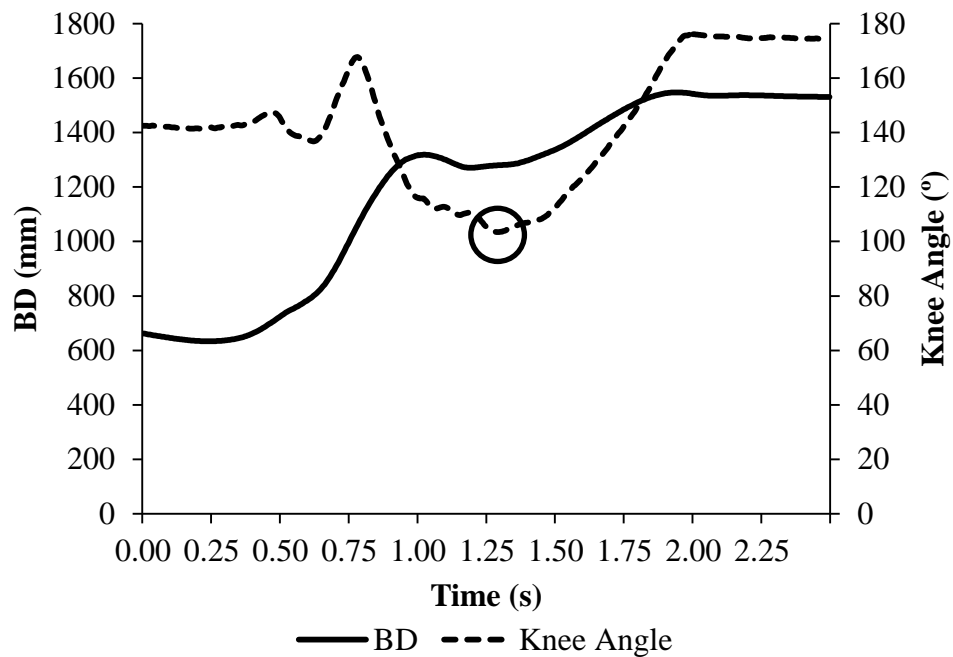


Figure 3.5. Typical BD and knee angle traces for a repetition of the hang clean (P4, HC70). The circled area indicates a rapid knee flexion prior the beginning of the 2nd upward phase.

3.4. Variable Calculation

For the upward phases of the back squat and hang clean, a number of variables were calculated to represent the displacement and energetic changes of the barbell and the body. To achieve the established aims of this study, it was determined that quantification of the greatest gain in Δ P.E of each segment of the body over the upward phase of a repetition was of interest. As a result, the potential energy of the body was quantified by summation of the maximum Δ P.E that each segment possessed during the movement phase of a repetition. For the back squat, maximum Δ P.E of all segments of the body and barbell occurred at the end of the upward phase, meaning the Δ P.E of the system at this time point is equal to that calculated via summing each segment individually. However, in the hang clean, there was not temporal synchronisation of maximum Δ P.E of each body segment or the barbell. Therefore, use of the term Δ P.E to describe the segments summed together is not a mechanically valid description of the

system and does not allow a single value to represent total gain in potential energy. Consequently, the term positive external work (PEW) will be utilised for energetic variables related to the hang clean as this mechanical terminology does not require temporal synchronicity. Rather it describes the sum of the maximum potential energies achieved by each segment individually, and allows expression of the total gain of potential energy within a single value.

Despite the difference in required terminology for the back squat and hang clean, the computational methods utilised for all variables are equivalent. Consequently, in the following outline of the equations employed for each variable, two versions are given with one using ΔPE terminology and one using PEW terminology. Each set of two equations are presented together, under the same equation number.

Barbell Displacement: Barbell displacement (BD) was calculated as the change in Z_{B-CoM} from the start to the end given phase of a repetition.

Barbell ΔPE : Barbell ΔPE was calculated as the product of the mass of the barbell (m_{bar}), BD and acceleration due to gravity (g):

$$Barbell \Delta PE = m_{bar} \times BD \times g \quad [Eq. 3.1]$$

A separate equation is not given for barbell PEW as barbell ΔPE only represents the displacement of a single CoM and is therefore not subject the necessity for temporal synchronisation. This definition also permits VL in the hang clean to be discussed on the same mechanical basis of ΔPE as the back squat. Displacement of the barbell was compared between barbell mass conditions, as opposed to barbell ΔPE , due to the confounding effect of barbell mass on systematic bias between conditions.

Body ΔPE and body PEW: The ΔPE of each segment of the body (segment ΔPE) was calculated from segment mass (m_s ; derived for participant body mass and segment parameters; de Leva, 1996a), the maximum change in Z_{S-CoM} for the segment from the start of the upward phase (segment displacement; d_s) and acceleration due to gravity:

$$Segment \Delta PE = m_s \times d_s \times g \quad [Eq. 3.2]$$

Body ΔPE and body PEW were calculated as the sum of the greatest ΔPE value of each segment during the upward phase of each exercise. Bilateral symmetry was assumed for the limbs:

$$\text{Body } \Delta PE = 2(\text{Foot } \Delta PE + \text{Shank } \Delta PE + \text{Thigh } \Delta PE + \text{Upper Arm } \Delta PE + \text{Lower Arm } \Delta PE + \text{Hand } \Delta PE) + \text{Torso } \Delta PE + \text{Head } \Delta PE$$

$$\text{Body } PEW = 2(\text{Foot } \Delta PE + \text{Shank } \Delta PE + \text{Thigh } \Delta PE + \text{Upper Arm } \Delta PE + \text{Lower Arm } \Delta PE + \text{Hand } \Delta PE) + \text{Torso } \Delta PE + \text{Head } \Delta PE \quad [\text{Eq. 3.3}]$$

Total ΔPE and total PEW : Total ΔPE and total PEW were defined as the sum of barbell ΔPE and body ΔPE or barbell ΔPE and body PEW for exercise, respectively:

$$\text{Total } \Delta PE = \text{Barbell } \Delta PE + \text{Body } \Delta PE$$

$$\text{Total } PEW = \text{Barbell } \Delta PE + \text{Body } PEW \quad [\text{Eq. 3.4}]$$

Body Mass Factor: Body mass factor (BMF) is the percentage of body mass (m_{bod}) that, if displaced by BD, would produce a ΔPE or PEW equal to measured body ΔPE or PEW . For the hang clean, BMF is given the subscript PEW (BMF_{PEW}) to denote the difference in mechanical basis of these variables:

$$\text{Body } \Delta PE = (m_{\text{bod}} \times \text{BMF}) \times BD \times g$$

$$\text{Body } PEW = (m_{\text{bod}} \times \text{BMF}_{PEW}) \times BD \times g \quad [\text{Eq. 3.5}]$$

Therefore,

$$\text{BMF} = \frac{\text{Body } \Delta PE}{m_{\text{bod}} \times BD \times g}$$

$$\text{BMF}_{PEW} = \frac{\text{Body } PEW}{m_{\text{bod}} \times BD \times g} \quad [\text{Eq. 3.6}]$$

Total ΔPE_{BMF} and total PEW_{BMF} : These are equal in value to total ΔPE and total PEW , respectively, but are calculated using the BMF and BMF_{PEW} values as follows,

$$\text{Total } \Delta PE_{BMF} = (m_{\text{bar}} + (m_{\text{bod}} \times \text{BMF})) \times BD \times g$$

$$\text{Total } PEW_{BMF} = (m_{\text{bar}} + (m_{\text{bod}} \times \text{BMF}_{PEW})) \times BD \times g \quad [\text{Eq. 3.7}]$$

System Mass Volume Load: System mass VL (SMVL) is the proposed alternative methodology to MDSVL that will allow for practically feasible incorporation of body mass within RT quantification. For a single repetition, measured in arbitrary units, SMVL is related to total ΔPE_{BMF} (and total PEW_{BMF}) by the following equation

(difference subscript designations are assigned to SMVL for the back squat and hang clean):

$$Total \Delta PE_{BMF} = k \times SMVL_{BS}$$

$$Total PEW_{BMF} = k \times SMVL_{HC} \quad [Eq. 3.8]$$

where, k (coefficient of proportionality) is equal to the product of BD and acceleration due to gravity.

Therefore,

$$SMVL_{BS} = \frac{Total \Delta PE_{BMF}}{k}$$

$$SMVL_{HC} = \frac{Total PEW_{BMF}}{k} \quad [Eq. 3.9]$$

Combination of Equation 3.7 and Equation 3.9 produces,

$$SMVL_{BS} = m_{bb} + (m_{bod} \times BMF)$$

$$SMVL_{HC} = m_{bb} + (m_{bod} \times BMF_{PEW}) \quad [Eq. 3.10]$$

The final representation of SMVL (Equation 3.10) is subject to the assumption that the k value for any given repetition is equal in magnitude to the k value from a strictly executed repetition of either back squat or hang clean for that individual. The validity of this assumption is related to the magnitude of variation and systematic bias in BD at or between different barbell masses and over sets of consecutive repetitions.

Maximum Dynamic Strength Volume Load: The MDSVL method proposed by McBride et al. (2009) was calculated for comparison to $SMVL_{BS}$:

$$MDSVL = m_{bar} + (m_{bod} \times 0.88) \quad [Eq. 3.11]$$

where 0.88 is the standard reference value utilized by McBride et al. (2009).

Error in estimating total ΔPE or total PEW created by two different assumptions was evaluated by comparison between the products of Equation 4 and Equation 7 for the three sets of six consecutive repetitions. The assumptions that were applied in Equation 7 and were a) constant BMF value for all participants (group mean from BS82 or HC82) and b) constant BMF value for all participants and constant BD value for each

individual (each participants mean BD from BS82 or HC82). For both assumptions, error was determined as the difference between measured (total ΔPE) and estimated (total ΔPE_{BMF}) values for each repetition in the three sets of six. Mean, standard deviation and range of the errors from each repetition were calculated for each participant. In addition, the error of the second assumption was also determined as the difference in the cumulative sum of total ΔPE for all 18 repetitions between total ΔPE and estimated total ΔPE_{BMF} .

3.5. Statistical Analysis

Coefficient of variation ($CV = SD/Mean \times 100$) was used to determine the variation of BD, body ΔPE , body PEW, BMF and BMF_{PEW} . It was calculated for each participant in each condition (single repetition conditions and sets of consecutive repetitions). It describes absolute reliability in that it does not account for an individuals' rank within a sample, and produces a value that is comparable between measurements different in scale or calibration (Hopkins, 2000). Due to theoretical issues preventing CV being assessed in relation to an analytical goal (Atkinson and Nevill, 1998), a particular magnitude of CV cannot be definitively concluded to represent high or low variation. Therefore, inference of meaning of CV is described in the context of the level of accuracy which can be expected if a variable was assumed constant between repetitions. Variation of BD was equal to variation of barbell ΔPE .

Analysis of variance (ANOVA) was used to examine for systematic bias in between barbell mass conditions and sets of repetitions for mean values of BD, body ΔPE , body PEW, BMF and BMF_{PEW} . For each participant, within-individual comparisons between the single repetitions at 70, 82 and 92 % of 1RM for the back squat and hang clean were made using a one-way single measures ANOVA for each variable. Group comparisons between each single repetition condition for back squat and hang clean were made using a one-way repeated measures ANOVA for the condition mean values and CV of each variable (Alberty et al., 2006). For each participant, within-individual comparisons between BSS1, BSS2 and BSS3 and HCS1, HCS2 and HCS3 were performed using a one-way repeated measures ANOVA. The same type of ANOVA (with 7 levels) was used to examine for differences between each repetition in either BSS1 or HCS1 compared with BS82 or HC82 at the group level. A two-way repeated measures ANOVA was used to examine for an interaction or effects of repetition and set over the

three sets for back squat and hang clean. Finally, a paired t-test compared measured and estimated cumulative sum of total ΔPE for the three sets of six consecutive repetitions.

The assumption of sphericity was examined using Machley's test. If significant asphericity was detected within the data set for an ANOVA comparison then either the Greenhouse-Geisser or Huynh-Feldt corrections were applied to the resulting p-value. In instances when the Greenhouse-Geisser epsilon value was > 0.75 then the Huynh-Feldt adjusted p-value was used, otherwise the Greenhouse-Geisser adjusted p-value was recorded (Girden, 1992, Atkinson, 2001). Where the ANOVA statistical test identified a significant difference, the levels between which any differences occurred were determined by making specific comparisons with a Ryan-Holm-Bonferroni adjustment (Ryan, 1960, Holm, 1979, Atkinson, 2002). This was achieved by using t-tests with the resulting p-values ranked in descending order of magnitude and multiplied by their rank. The significance level for all statistical tests was set at $p < 0.05$.

The ICC statistic was used to examine the between-participant consistency of each repetition within BSS1, BSS2 and BSS3 and HC70, HC82 and HC92. Based on the terminology and recommendations of McGraw and Wong (1996) the ICC(C,1) variant of the calculation technique was used.

CHAPTER 4: RESULTS

4.1. Back Squat

4.1.1. Barbell Mass Conditions

In the back squat all participants displaced the barbell over similar ranges relative to their height, and BD variation (CV) ranged from 0.4 to 4.5 % across all barbell mass conditions (Table 4.1). Individual patterns of change in CV magnitude between conditions were not consistent across the group. The variation of body Δ PE for individual participants in each barbell mass condition ranged from 0.6 to 5.0 % (Table 4.1). Similarly to BD, no consistent patterns of change in CV were detected as barbell mass increased for the group. When examined statistically, no significant difference in CV between barbell mass conditions for BD ($p = 0.671$) or body Δ PE ($p = 0.797$) were identified for the group.

The individual participant comparisons of BD revealed significant differences between barbell mass conditions for three participants (P1, P2 and P8; Table 4.1). The post-hoc test identified for all these participants that BD in BS92 was significantly lower than in the other conditions. For body Δ PE, individual participant comparisons found overall significant differences for four participants (P1, P2, P5 and P8; Table 4.1), with the post-hoc analysis identifying significant reductions in body Δ PE as barbell mass increased.

The group level comparison that examined for the effects of barbell mass on back squat BD revealed a significant difference ($p = 0.024$). However, the post-hoc test could not identify the location of this effect (Table 4.1). The same group level comparison also identified an overall significant difference for body Δ PE across barbell mass conditions ($p = 0.003$), with the post-hoc test showing BS92 was significantly lower compared with BS70 ($p = 0.019$).

Table 4.1. Mean, SD and CV data for BD and body Δ PE from the five single repetitions of the back squat in each barbell mass condition for each participant. ^a denotes condition significantly lower compared with BS70 and ^b denotes condition significantly lower compared with BS82.

	BD (mm) - Mean \pm SD (CV %)			Body Δ PE (J) - Mean \pm SD (CV %)		
	BS70	BS82	BS92	BS70	BS82	BS92
P1	572 \pm 11 (1.9)	555 \pm 15 (2.7)	520 \pm 16 (3.1) ^{a,b}	331 \pm 8 (2.4)	316 \pm 11 (3.5) ^a	294 \pm 9 (3.1) ^{a,b}
P2	650 \pm 7 (1.1)	647 \pm 12 (1.9)	625 \pm 6 (1.0) ^{a,b}	377 \pm 6 (1.6)	374 \pm 10 (2.7)	360 \pm 2 (0.6) ^{a,b}
P3	639 \pm 29 (4.5)	651 \pm 10 (1.5)	667 \pm 18 (2.7)	381 \pm 19 (5.0)	384 \pm 6 (1.6)	390 \pm 12 (3.1)
P4	745 \pm 11 (1.5)	738 \pm 4 (0.5)	726 \pm 20 (2.8)	504 \pm 6 (1.2)	498 \pm 4 (0.8)	485 \pm 13 (2.7)
P5	621 \pm 11 (1.8)	622 \pm 10 (1.6)	613 \pm 4 (0.7)	300 \pm 6 (2.0)	297 \pm 6 (2.0)	288 \pm 2 (0.7) ^{a,b}
P6	624 \pm 18 (2.9)	606 \pm 18 (3.0)	621 \pm 22 (3.5)	334 \pm 11 (3.3)	321 \pm 11 (3.4)	329 \pm 15 (4.6)
P7	690 \pm 13 (1.9)	694 \pm 15 (2.2)	672 \pm 22 (3.3)	389 \pm 7 (1.8)	388 \pm 9 (2.3)	369 \pm 14 (3.8)
P8	613 \pm 17 (2.8)	610 \pm 11 (1.8)	580 \pm 19 (3.3) ^{a,b}	364 \pm 7 (1.9)	360 \pm 8 (2.2)	341 \pm 10 (2.9) ^{a,b}
P9	715 \pm 30 (4.2)	680 \pm 14 (2.1)	688 \pm 9 (1.3)	464 \pm 21 (4.5)	437 \pm 12 (2.7)	442 \pm 6 (1.4)
P10	781 \pm 5 (0.6)	774 \pm 13 (1.7)	768 \pm 3 (0.4)	540 \pm 4 (0.7)	539 \pm 5 (0.9)	540 \pm 3 (0.6)
Group Mean	665 \pm 65	658 \pm 64	648 \pm 70	398 \pm 76	391 \pm 76	384 \pm 79 ^a

4.1.2. Sets of Consecutive Repetitions

A similar range of magnitude and variation of BD and body Δ PE were found for all participants in the sets of consecutive repetitions of the back squat compared with the individual barbell mass conditions (Table 4.2). For BD, CV ranged from 0.6 to 4.2 % and the range of CV for body Δ PE was 0.8 to 4.4 %. No group level differences in CV across the three sets of six repetitions were found ($p = 0.135$ and $p = 0.216$ for BD and body Δ PE, respectively).

There were significant differences in BD for two participants' individual comparisons (P4 and P9) between the three sets of six repetitions (Table 4.2). For P4 the post-hoc test identified that BD in BSS1 was significantly greater than other sets, and for P9 BSS3 was significantly lower than BSS2. When examining body Δ PE, there were significant differences found for three participants (P4, P8 and P9) and these were between different sets for each participant (Table 4.2).

An overall group significant difference for BD was revealed for consecutive repetitions within BSS1 compared with BS82 ($p = 0.003$; Figure 4.1), although the post-hoc test could not identify any individual comparisons for which a significant difference existed. Similarly, an overall significant group difference for body Δ PE was found for BSS1 ($p < 0.001$; Figure 4.2), although for this comparison the post-hoc test identified BSS1 repetition 1 to be significantly lower compared with body Δ PE in BS82 ($p = 0.013$). The ICC(C,1) values for BD were 0.949, 0.957 and 0.960 for BSS1, BSS2 and BSS3, respectively. For body Δ PE, the ICC values were 0.994, 0.989 and 0.991, respectively.

The two-way repeated measures ANOVA revealed no significant effects of multiple sets of consecutive repetitions of back squat on either BD or body Δ PE ($p = 0.209$ and $p = 0.648$, respectively), although there were significant effects of consecutive repetitions within a set ($p = 0.014$ and $p = 0.029$, respectively). Overall, the interaction comparison found there were no significant effects over the course of three sets of six consecutive repetitions on BD or body Δ PE ($p = 0.502$ and $p = 0.402$, respectively).

Table 4.2. Mean, SD and CV data for BD and body Δ PE from the three sets of six consecutive repetitions of back squat at 82 % of 1RM for each participant. ^a denotes set significantly lower compared with BSS1 and ^b denotes set significantly lower compared with BSS2.

	BD (mm) - Mean \pm SD (CV %)			Body Δ PE (J) - Mean \pm SD (CV %)		
	BSS1	BSS2	BSS3	BSS1	BSS2	BSS3
P1	528 \pm 21 (4.0)	537 \pm 15 (2.8)	523 \pm 22 (4.2)	302 \pm 12 (4.0)	301 \pm 9 (3.0)	294 \pm 13 (4.4)
P2	611 \pm 7 (1.1)	610 \pm 16 (2.6)	614 \pm 12 (2.0)	355 \pm 5 (1.4)	351 \pm 11 (3.1)	357 \pm 7 (2.0)
P3	649 \pm 17 (2.6)	645 \pm 12 (1.9)	644 \pm 13 (2.0)	384 \pm 7 (1.8)	387 \pm 9 (2.3)	388 \pm 3 (0.8)
P4	721 \pm 7 (1.0)	690 \pm 18 (2.6) ^a	692 \pm 18 (2.6) ^a	487 \pm 5 (1.0)	468 \pm 8 (1.7) ^a	468 \pm 10 (2.1) ^a
P5	611 \pm 17 (2.8)	618 \pm 19 (3.1)	613 \pm 15 (2.4)	289 \pm 9 (3.1)	292 \pm 11 (3.8)	290 \pm 8 (2.8)
P6	609 \pm 9 (1.5)	612 \pm 15 (2.5)	610 \pm 11 (1.8)	323 \pm 8 (2.5)	324 \pm 10 (3.1)	325 \pm 5 (1.5)
P7	664 \pm 9 (1.4)	662 \pm 12 (1.8)	667 \pm 12 (1.8)	365 \pm 7 (1.9)	361 \pm 8 (2.2)	368 \pm 6 (1.6)
P8	581 \pm 16 (2.8)	580 \pm 23 (4.0)	561 \pm 18 (3.2)	339 \pm 8 (2.4)	342 \pm 9 (2.6)	326 \pm 8 (2.5) ^{a,b}
P9	695 \pm 10 (1.4)	704 \pm 8 (1.1)	681 \pm 11 (1.6) ^b	444 \pm 7 (1.6)	454 \pm 6 (1.3)	442 \pm 4 (0.9) ^b
P10	791 \pm 5 (0.6)	786 \pm 12 (1.5)	792 \pm 14 (1.8)	549 \pm 8 (1.5)	552 \pm 9 (1.6)	556 \pm 11 (2.0)
Group Mean	646 \pm 73	644 \pm 69	640 \pm 73	384 \pm 81	383 \pm 80	381 \pm 82

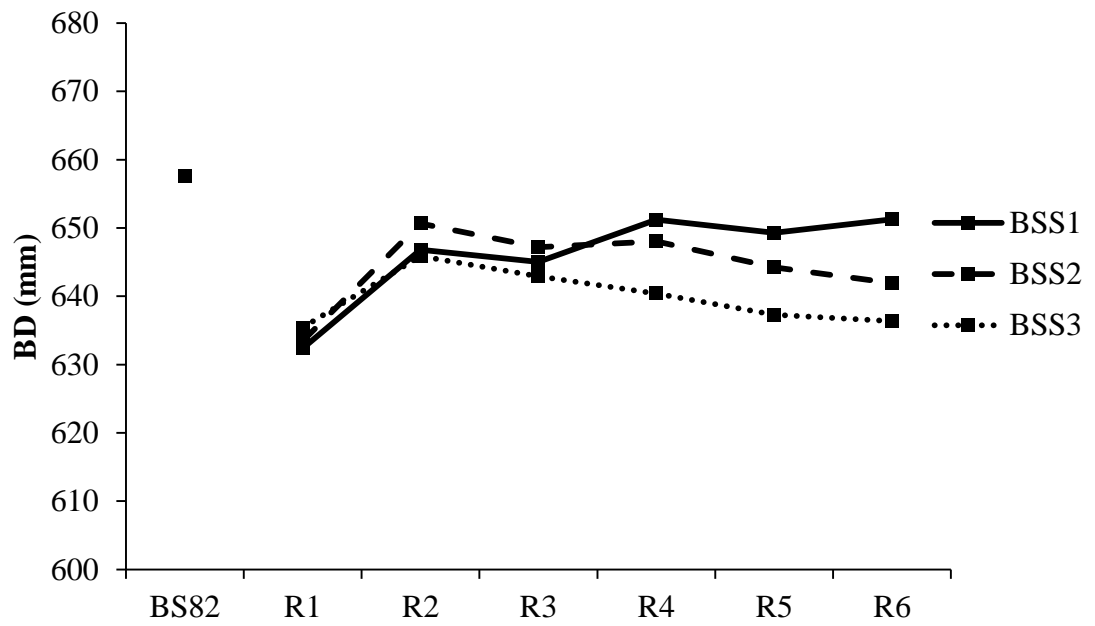


Figure 4.1. Mean BD for each repetition in the three sets of consecutive repetitions compared with mean BS82. An overall significant difference between repetitions was found for BSS1. Error bars are not displayed due to the confounding factor of participant height.

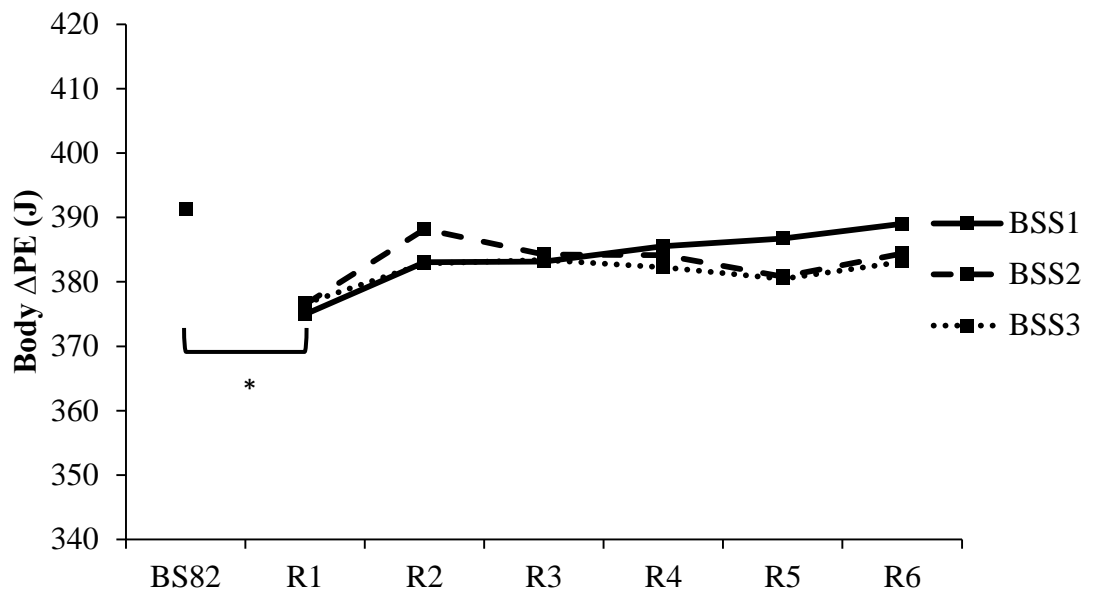


Figure 4.2. Mean body Δ PE for each rep in the three sets of consecutive repetitions compared with BS82. Overall significant differences were found for S1. Only BSS1 R1 was found to be significantly different to BS82 (*). Error bars are not included due to the confounding factor of participant body mass.

4.1.3. BMF and SMVL

The individual participant intra-barbell mass condition CV values for BMF ranged from 0.3 to 1.3 % in the back squat (Table 4.3). No patterns of CV change across the three conditions were identified for the group ($p = 0.470$). The individual participant comparisons between barbell mass conditions showed that for five of the ten participants (P1, P3, P5, P7 and P9) BMF was significantly lower as barbell mass increased (Table 4.3). Conversely, for one participant (P10) BMF was significantly increased between BS70 and BS92 conditions. Group comparison of BMF between barbell mass conditions showed a significant overall difference ($p = 0.011$; Table 4.3) and the post-hoc test revealed BS70 to be significantly greater than BS82 ($p = 0.017$) and BS92 ($p = 0.025$).

Table 4.3. Mean, SD and CV data for BMF from the five single repetitions of the back squat in each barbell mass condition for each participant and the group. ^a denotes condition significantly lower compared with BS70, ^b denotes condition significantly lower compared with BS82 and ^c denotes condition significantly greater compared with BS70.

	BMF (%) - Mean \pm SD (CV %)		
	BS70	BS82	BS92
P1	69.0 \pm 0.4 (0.6)	67.9 \pm 0.6 (0.9) ^a	67.4 \pm 0.9 (1.3) ^a
P2	68.1 \pm 0.5 (0.7)	67.8 \pm 0.5 (0.7)	67.6 \pm 0.4 (0.6)
P3	68.3 \pm 0.3 (0.4)	67.5 \pm 0.3 (0.4) ^a	66.8 \pm 0.8 (1.2) ^a
P4	69.5 \pm 0.9 (1.3)	69.3 \pm 0.3 (0.4)	68.6 \pm 0.2 (0.3)
P5	69.9 \pm 0.3 (0.4)	69.0 \pm 0.5 (0.7) ^a	68.0 \pm 0.6 (0.9) ^{a,b}
P6	67.4 \pm 0.3 (0.4)	66.8 \pm 0.5 (0.7)	66.9 \pm 0.8 (1.2)
P7	69.0 \pm 0.2 (0.3)	68.6 \pm 0.2 (0.3) ^a	67.4 \pm 0.6 (0.9) ^{a,b}
P8	68.3 \pm 0.9 (1.3)	67.8 \pm 0.9 (1.3)	67.6 \pm 0.7 (1.0)
P9	69.9 \pm 0.3 (0.4)	69.2 \pm 0.5 (0.7)	69.1 \pm 0.2 (0.3) ^a
P10	68.6 \pm 0.2 (0.3)	69.1 \pm 0.6 (0.9)	69.8 \pm 0.3 (0.4) ^c
Group Mean	68.8 \pm 0.9 (1.3)	68.3 \pm 1.0 (1.5) ^a	67.9 \pm 1.1 (1.6) ^a

When assuming BMF to be constant (BS82 group mean value), the mean error in calculation of total ΔPE_{BMF} , compared with total ΔPE , from each repetition in the three

sets was 0 ± 8 J (Figure 4.3). The mean total ΔPE values for each participant for the three sets of six repetitions at 82 % of 1RM are given in Figure 4.4.

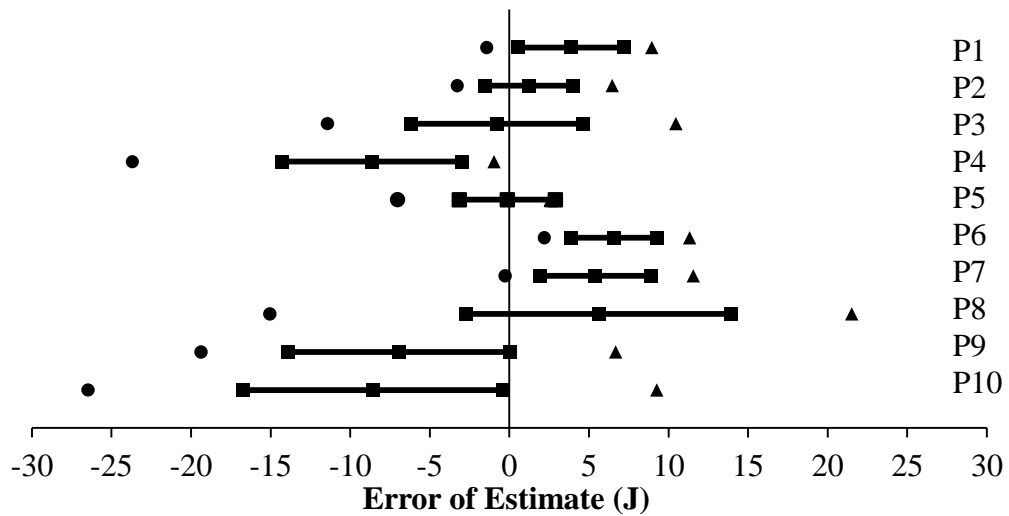


Figure 4.3. Error of total ΔPE_{BMF} for all repetitions in BSS1, BSS2 and BSS3 for each participant when BMF assumed constant (BS82 group mean value). Mean (\pm SD) are represented by closed boxes and minimum and maximum range are represented by closed circles and triangles, respectively.

For the sets of consecutive repetitions, the assumption that BD was constant (individual participant mean value from BS82), combined with constant BMF (BS82 group mean value) in estimation of total ΔPE_{BMF} resulted in a group mean value of 21362 ± 4747 J for all 18 repetitions cumulatively (Figure 4.5). The measured value was 20871 ± 4693 J, and there was no significant difference between the actual and estimated values ($p = 0.079$). The estimation of total ΔPE_{BMF} resulted in a group mean error for a single repetition of 27 ± 50 J, whilst the overall error value for 18 repetitions was 491 ± 785 J. When expressed relative to the number of repetitions, the overall mean error was equivalent to the ΔPE value of 0.4 ± 0.6 repetitions (range -0.5 to 1.2) or 2.5 ± 3.5 % when displayed as a percentage. The group mean $SMVL_{BS}$ and $MDSVL$ for one repetition were 183 ± 30 a/u and 201 ± 30 a/u and for 18 repetitions were 3297 ± 544 a/u and 3610 ± 569 a/u, respectively.

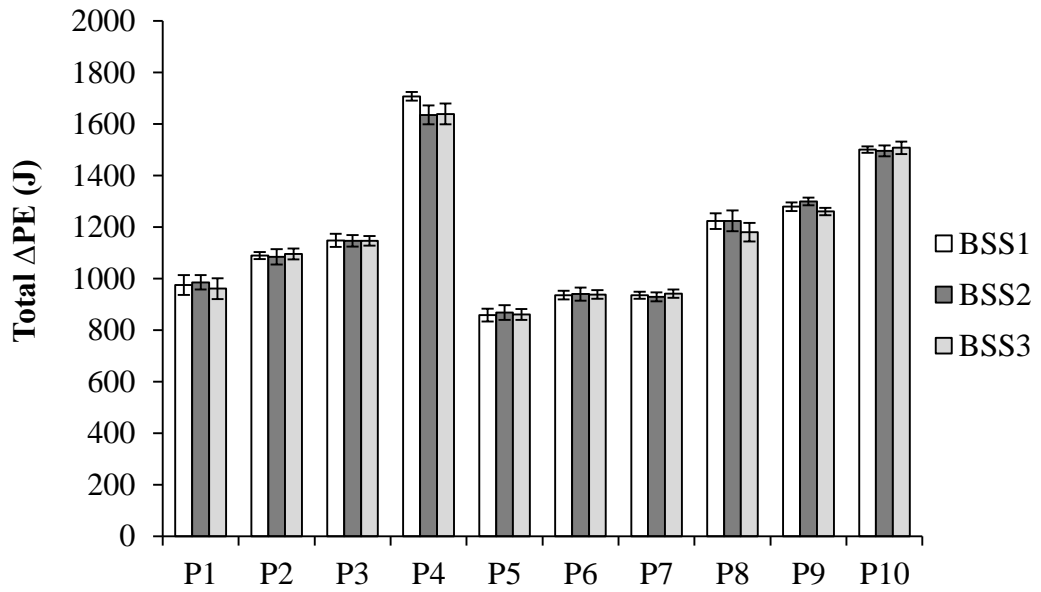


Figure 4.4. Mean total ΔPE (\pm SD) for each participant in BSS1, BSS2 and BSS3.

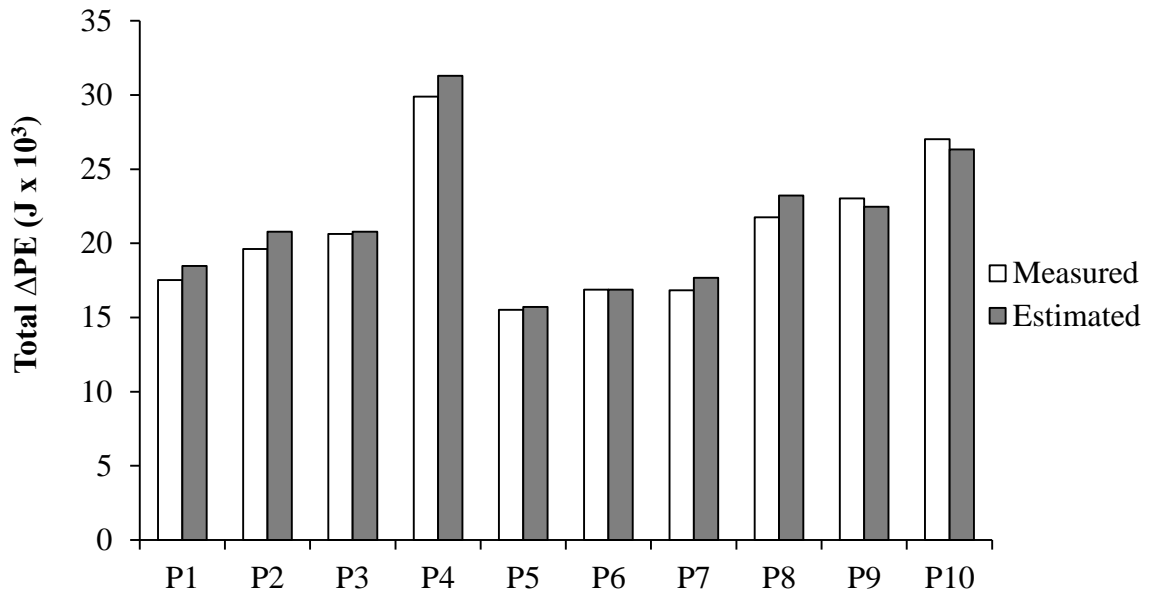


Figure 4.5. Total ΔPE for the three sets of six consecutive repetitions compared with total ΔPE_{BMF} when calculated using individual participant mean BD and group mean BMF values from BS82.

4.2. Hang Clean

Three of the eight participants could not complete the full experimental protocol of three sets of six repetitions of the hang clean. Participant P1 completed 6, 5 and 4 repetitions in HCS1, HCS2 and HCS3, respectively. For P6 only two sets, one of 5 repetitions and one of 4, were completed and P10 only completed 4 repetitions in each of the 3 sets. Consequently, for the 2-way repeated measured ANOVA and ICC calculations, the sets were analysed as consisting of the first four consecutive repetitions for all participants and P6 was omitted to eliminate issues of missing data. All data was analysed prior to this comparison to maximise the size of the sample.

4.2.1. Barbell Mass Conditions

The individual mean, SD and CV of BD and body PEW for each participant in each barbell mass condition of the hang clean are given in Table 4.4. For BD, the range of CV was from 0.7 to 6.0 % and for body PEW, the range was 0.6 to 8.0 %. No significant difference in CV of BD ($p = 0.858$) between barbell mass conditions was identified. Similarly, there was no significant difference ($p = 0.653$) for CV of body PEW between barbell mass conditions.

Individual participant comparisons of BD revealed significant differences for all participants between barbell mass conditions (Table 4.4). Post-hoc analysis showed that for five participants all conditions were significantly different from each other, with BD decreasing in magnitude as barbell mass increased. Significant differences in body PEW between barbell mass conditions were found for three participants (P1, P4 and P9; Table 4.4). For P1 and P4 body PEW decreased as barbell mass increased whilst for P9, body PEW increased with barbell mass.

Group level comparison of BD across hang clean barbell mass conditions revealed a significant difference ($p = 0.010$). It was determined that HC92 was significantly lower than HC70 ($p = 0.019$) and HC82 ($p = 0.002$). There was no significant difference for the group in body PEW across barbell mass conditions ($p = 0.836$).

Comparison of BD between the 1st upward phase, downward phase and 2nd upward phase showed considerable intra- and inter-individual differences (Figure 4.6). There were no significant differences between conditions when downward phase BD was expressed as a percentage of 1st upward phase BD (HC70 = 7 ± 4 %; HC82 = 9 ± 4 %;

HC92 = 16 ± 12 %). When 2nd upward phase BD was expressed as a percentage of 1st upward phase BD, there was an overall significant difference between barbell mass conditions for the group ($p = 0.012$). The post-hoc test revealed that HC92 (54 ± 21 %) was significantly greater than HC70 (31 ± 10 %; $p = 0.028$) and HC82 (39 ± 12 %; $p = 0.016$).

When duration of the downward phase was expressed as a percentage of 1st upward phase, there was no significant difference for the group between conditions ($p = 0.055$; HC70 = 25 ± 10 %; HC82 = 34 ± 11 %; HC92 = 44 ± 23 %). Conversely, there was a significant group effect for the 2nd upward phase ($p = 0.018$). However, the location of significance between HC70 (80 ± 28 %), HC82 (85 ± 30 %) and HC92 (102 ± 48 %) could not be identified.

Table 4.4. Mean, SD and CV data for BD and body PEW from the five single repetitions of the hang clean in each barbell mass condition for each participant. ^a denotes condition significantly lower compared with HC70, ^b denotes condition significantly lower compared with HC82, ^c denotes condition significantly higher compared with HC70 and ^d denotes condition significantly higher compared with HC82.

	BD (mm) - Mean \pm SD (CV %)			Body PEW (J) - Mean \pm SD (CV %)		
	HC70	HC82	HC92	HC70	HC82	HC92
P1	764 \pm 19 (2.5)	701 \pm 15 (2.1) ^a	651 \pm 18 (2.8) ^{a,b}	159 \pm 7 (4.4)	150 \pm 9 (6.0)	144 \pm 5 (3.5) ^a
P2	857 \pm 21 (2.5)	832 \pm 30 (3.6)	783 \pm 13 (1.7) ^{a,b}	212 \pm 11 (5.2)	213 \pm 8 (3.8)	206 \pm 9 (4.4)
P3	735 \pm 23 (3.1)	709 \pm 14 (2.0)	664 \pm 13 (2.0) ^{a,b}	164 \pm 13 (7.9)	168 \pm 1 (0.6)	166 \pm 8 (4.8)
P4	682 \pm 19 (2.8)	608 \pm 20 (3.3) ^a	573 \pm 11 (1.9) ^{a,b}	184 \pm 8 (4.3)	167 \pm 7 (4.2) ^a	166 \pm 4 (2.4) ^a
P5	652 \pm 11 (1.7)	600 \pm 21 (3.5) ^a	569 \pm 15 (2.6) ^{a,b}	107 \pm 3 (2.8)	104 \pm 8 (7.7)	106 \pm 5 (4.7)
P6	752 \pm 21 (2.8)	709 \pm 20 (2.8) ^a	643 \pm 19 (3.0) ^{a,b}	173 \pm 6 (3.5)	175 \pm 7 (4.0)	176 \pm 4 (2.3)
P9	704 \pm 42 (6.0)	768 \pm 30 (3.9) ^c	771 \pm 20 (2.6) ^c	156 \pm 12 (7.7)	174 \pm 14 (8.0)	203 \pm 8 (3.9) ^{c,d}
P10	802 \pm 8 (1.0)	731 \pm 5 (0.7) ^a	687 \pm 25 (3.6) ^{a,b}	206 \pm 5 (2.4)	199 \pm 4 (2.0)	194 \pm 9 (4.6)
Group Mean	735 \pm 66	704 \pm 80	665 \pm 81 ^{a,b}	165 \pm 31	164 \pm 32	167 \pm 33

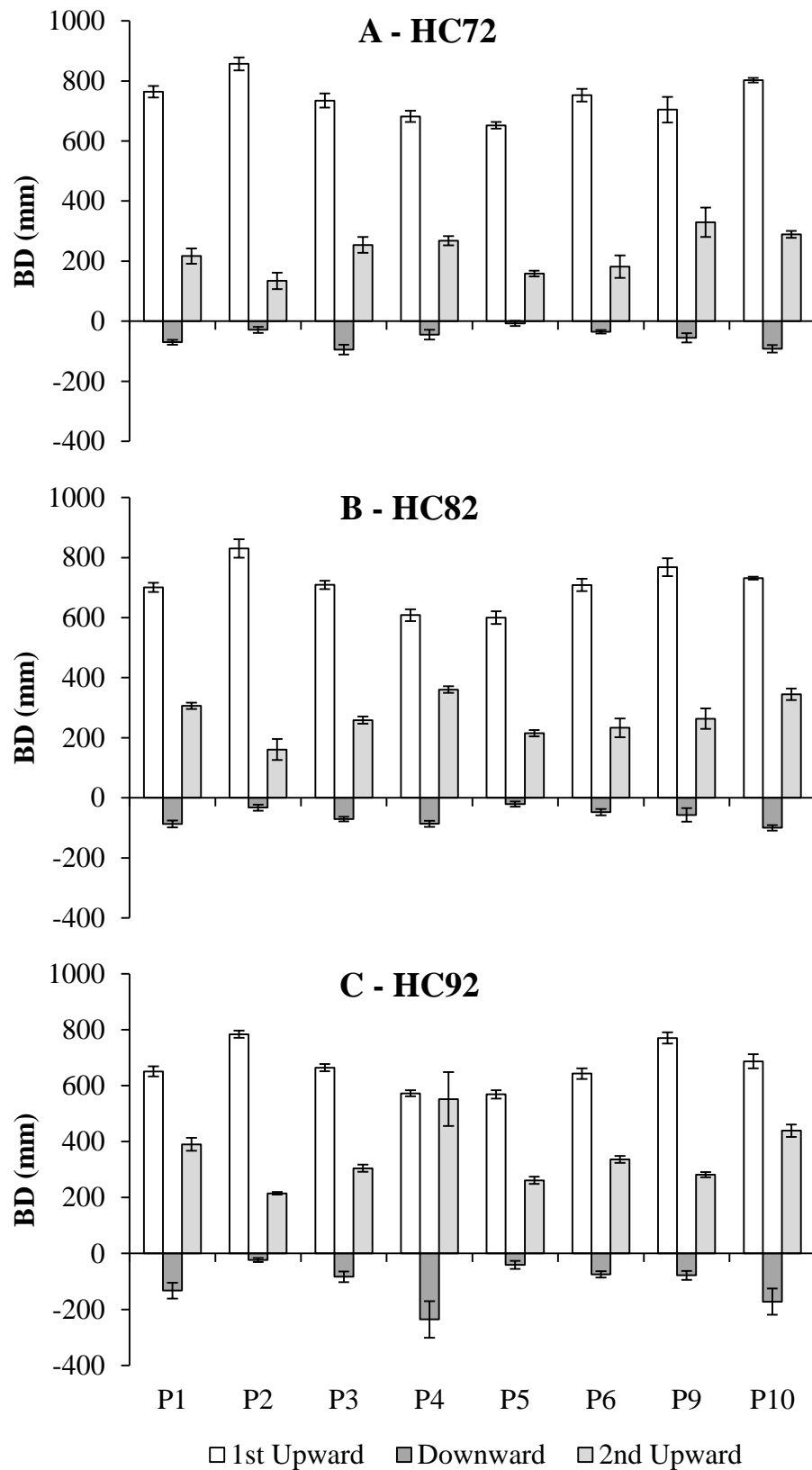


Figure 4.6. Comparison of mean barbell displacement (\pm SD) for 1st upward phase, downward phase and 2nd upward phase in the hang clean for each participant in HC70 (A), HC82 (B) and HC92 (C).

4.2.2. Sets of Consecutive Repetitions

Across the three sets of consecutive repetitions the individual within-set variation (CV) of BD ranged from 1.3 to 6.2 %, and for body PEW the range was 2.5 to 12.4 % (Table 4.5). As with CV values with all other variables, neither showed a group level effect of set on CV ($p = 0.546$ and $p = 0.488$, respectively). Additionally, no consistent pattern of change in CV between sets or conditions was established on an individual basis.

Individual comparisons between sets to detect systematic bias revealed a significant difference for BD for P5 (Table 4.5), and it was identified that BD in HCS1 was significantly lower than HCS2 and HCS3 by the post-hoc test. No significant differences were found for body PEW for any participants.

In examining for systematic effects of a set of consecutive repetitions compared with single repetitions, an overall group significant difference for BD was revealed within HCS1 compared with HC82 ($p = 0.043$; Figure 4.7). The post-hoc test identified that BD for HCS1 repetition 1 was significantly lower than HC82 ($p = 0.033$). Conversely, no significant group difference for body PEW was found for any repetition in HCS1 compared with BS82 ($p = 0.488$; Figure 4.8). The between-individual consistency ICCs for BD were 0.950, 0.945 and 0.956 for HCS1, HCS2 and HCS3, respectively. For body PEW, the ICC values were 0.913, 0.932 and 0.956, respectively.

For BD, there was a significant interaction effect of repetition and set identified for the seven participants that completed four repetitions in each set ($p = 0.020$). However, the opposite was found for body PEW as there was no interaction effect of set and repetition ($p = 0.395$). None of the set and repetition comparisons over HCS1, HCS2 and HCS3 showed significant differences for either BD or body PEW.

Table 4.5. Mean, SD and CV data for BD and body PEW from all consecutive repetitions of hang clean from each set for each participant.

^a denotes condition significantly higher compared with HCS1.

	BD (mm) - Mean \pm SD (CV %)			Body PEW (J) - Mean \pm SD (CV %)		
	HCS1	HCS2	HCS3	HCS1	HCS2	HCS3
P1	676 \pm 42 (6.2)	678 \pm 29 (4.3)	685 \pm 28 (4.1)	145 \pm 18 (12.4)	156 \pm 9 (5.7)	152 \pm 5 (3.3)
P2	815 \pm 41 (5.1)	786 \pm 29 (3.7)	801 \pm 42 (5.2)	206 \pm 16 (7.8)	205 \pm 8 (4.1)	205 \pm 8 (4.1)
P3	700 \pm 23 (3.3)	691 \pm 15 (2.1)	685 \pm 27 (3.9)	163 \pm 6 (3.9)	162 \pm 9 (5.6)	167 \pm 6 (3.7)
P4	604 \pm 21 (3.5)	602 \pm 10 (1.7)	591 \pm 16 (2.8)	167 \pm 5 (2.8)	168 \pm 6 (3.9)	171 \pm 7 (4.3)
P5	552 \pm 7 (1.3)	583 \pm 21 (3.6) ^a	594 \pm 24 (4.1) ^a	99 \pm 5 (4.6)	106 \pm 12 (10.9)	108 \pm 11 (10.3)
P6	666 \pm 21 (3.2)	662 \pm 11 (1.7)		179 \pm 4 (2.5)	181 \pm 6 (3.1)	
P9	804 \pm 23 (2.9)	844 \pm 33 (3.9)	820 \pm 26 (3.2)	213 \pm 12 (5.7)	216 \pm 10 (4.8)	217 \pm 6 (2.6)
P10	692 \pm 11 (1.6)	693 \pm 21 (3.0)	686 \pm 22 (3.3)	182 \pm 7 (3.9)	178 \pm 5 (2.7)	180 \pm 7 (4.1)
Group Mean	688 \pm 89	693 \pm 87	695 \pm 90	169 \pm 36	172 \pm 34	171 \pm 36

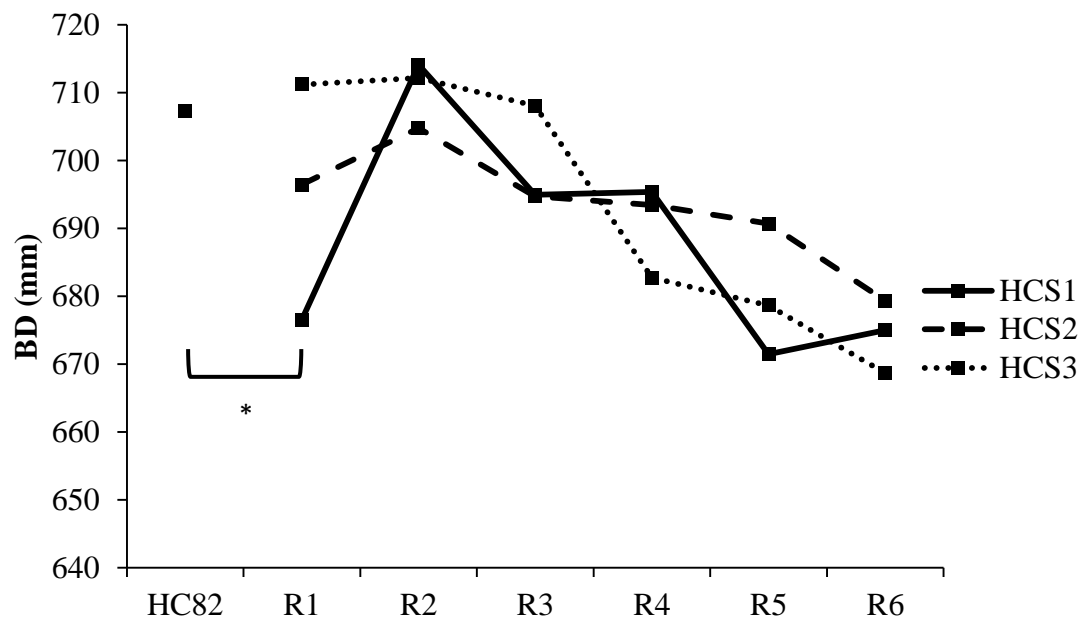


Figure 4.7. Mean BD for the three sets of consecutive repetitions compared with HC82. HCS1 R1 was found to be significantly different to HC82 (*). Error bars are not included due to confounding nature of participant height.

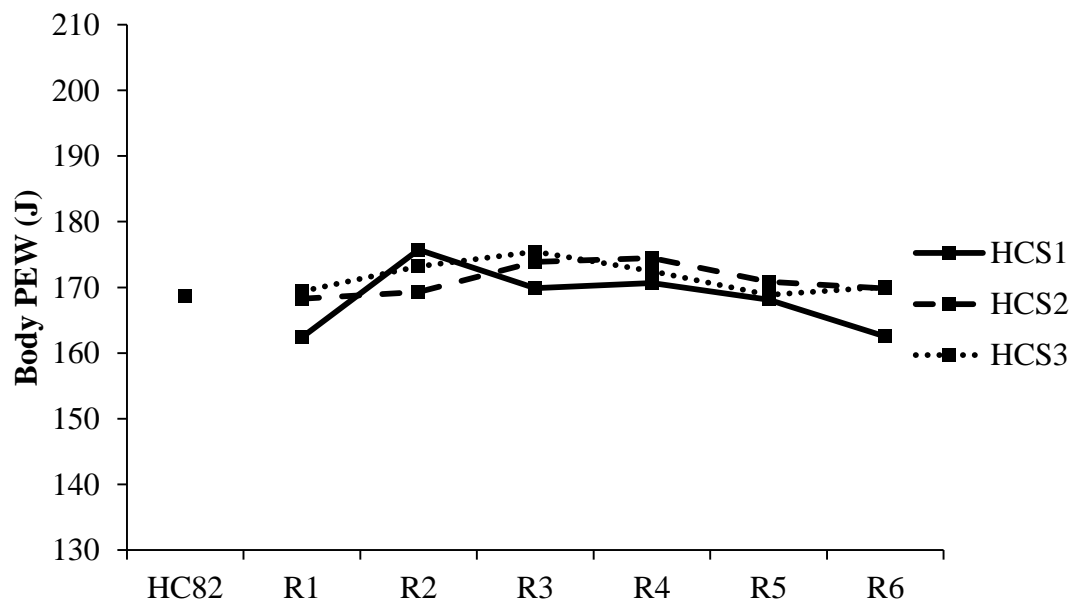


Figure 4.8. Mean body PEW for the three sets of consecutive repetitions compared with HC82. Error bars are not included due to confounding nature of participant mass.

4.2.3. BMF and SMVL

The variation of hang clean BMF_{PEW} within a single condition produced CV values ranging from 1.3 to 5.9 % (Table 4.6). Similar to back squat BMF, there was no significant group level effect of barbell mass on CV detected ($p = 0.471$). Also, no consistent patterns of CV change between conditions were found on an individual basis.

The individual participant comparisons between barbell mass conditions showed systematic bias in hang clean BMF_{PEW} magnitude for seven of the eight participants (Table 4.6). Post-hoc analysis determined that for all of these participants BMF_{PEW} was significantly greater as barbell mass increased, although specific comparisons for which differences existed varied between individuals (Table 4.6). Group level comparison of BMF_{PEW} between barbell mass condition showed a significant overall difference ($p < 0.001$) and the post-hoc test revealed BMF_{PEW} was significantly greater as barbell mass increased (Table 4.6).

Further data are not presented here for the hang clean due to the results presented above meaning that the assumptions required for use of the BMF_{PEW} and SMVL_{HC} methods are not valid. They are included in Annex 1 for reference.

Table 4.6. Mean, SD and CV data for BMF_{PEW} from the five single repetitions of the hang clean in each barbell mass condition for each participant and the group. ^a denotes condition significantly greater compared with HC70 and ^b denotes condition significantly greater compared with HC82.

BMF _{PEW} (%) - Mean \pm SD (CV %)			
	HC70	HC82	HC92
P1	24.7 \pm 0.5 (2.0)	25.4 \pm 1.1 (4.3)	26.3 \pm 0.5 (1.9) ^a
P2	29.1 \pm 1.4 (4.8)	30.1 \pm 1.6 (5.3)	30.9 \pm 0.9 (2.9)
P3	25.5 \pm 1.5 (5.9)	27.1 \pm 0.6 (2.2)	28.6 \pm 1.1 (3.8) ^a
P4	27.8 \pm 0.8 (2.9)	28.2 \pm 0.6 (2.1)	29.7 \pm 0.4 (1.3) ^{a,b}
P5	23.8 \pm 0.3 (1.3)	24.9 \pm 1.3 (5.2)	27.0 \pm 0.6 (2.2) ^{a,b}
P6	29.1 \pm 0.6 (2.1)	31.1 \pm 0.4 (1.3) ^a	34.6 \pm 1.0 (2.9) ^{a,b}
P9	23.9 \pm 0.8 (3.3)	24.4 \pm 1.1 (4.5)	28.3 \pm 1.1 (3.9) ^{a,b}
P10	25.4 \pm 0.8 (3.1)	27.0 \pm 0.7 (2.6) ^a	28.0 \pm 0.4 (1.4) ^{a,b}
Group Mean	26.3 \pm 2.4	27.3 \pm 2.6 ^a	29.4 \pm 2.7 ^{a,b}

4.3. Barbell Marker Reliability

Barbell sleeve end vertical coordinate marker reliability data is presented in Table 4.4 for all participants from the single repetitions of the back squat and hang clean.

Table 4.7. Mean for all single repetitions for each participant of mean trial CV of vertical coordinate of sleeve end from the 6 possible calculation methods.

CV (%) - Mean \pm SD		
	Back Squat	Hang Clean
P1	0.2 \pm 0.0	0.5 \pm 0.1
P2	0.5 \pm 0.2	0.4 \pm 0.1
P3	0.4 \pm 0.1	0.7 \pm 0.1
P4	0.4 \pm 0.1	0.4 \pm 0.1
P5	0.4 \pm 0.1	0.3 \pm 0.1
P6	0.3 \pm 0.0	0.6 \pm 0.0
P7	0.2 \pm 0.0	
P8	0.5 \pm 0.1	
P9	0.2 \pm 0.0	0.6 \pm 0.1
P10	0.4 \pm 0.1	0.7 \pm 0.1

CHAPTER 5: DISCUSSION

5.1. Introduction

The present study aimed to enhance the scientific basis of practically feasible methods of RT quantification. In approaching these aims, research questions 1-3 were devised to examine variability, systematic bias and error of estimation of energetic variables between single and consecutive repetitions of the back squat and hang clean exercises.

The main findings indicated that for the back squat, a good degree of accuracy was found when a constant BMF value was used with measured BD to estimate total ΔPE . The level of accuracy reduced when a constant BD value was used for each individual, although this was related to differences between single and consecutive repetitions. Consequently, if individual assessment of bias between different relative barbell masses is conducted, then the SMVL method can be described as a representation of total ΔPE in RT. For the present sample of experienced RT males, the accuracy of this representation was found to be $2.5 \pm 3.5 \%$.

Considerable intra- and inter-individual variation in systematic bias for the hang clean meant that the data indicated the accuracy, and therefore practical applicability, of this methodology was low. This finding is potentially due to the greater complexity of the movement pattern and importance of barbell velocity to successful execution of the exercise.

In this chapter each of the research questions and their subsections are directly addressed considering the presented data. The practical implications of the resulting conclusions are considered, with specific emphasis on application by coaches and sports science practitioners. The discussion is concluded by examination of measurement considerations, directions for future research and a final thesis conclusion.

5.2. Addressing the Research Questions

The research questions were devised to examine the validity of assuming BD to be constant and therefore consider VL as a representation of ΔPE . Moreover, the first measurement of ΔPE of the segments of the body in the context to RT quantification was incorporated within the scope of the investigation. This was to facilitate deriving a

mechanically valid standard reference value to allow inclusion of body Δ PE or PEW in determining the external training load of RT for athletes, a method termed SMVL. As established in the methodology, to maintain the mechanical accuracy of the investigation into the hang clean, the terminology of PEW was introduced instead of Δ PE. The alternate terminology of PEW is employed when answering the research questions, although it is not explicitly incorporated within them. The data presented separately for each of the exercises is combined to answer each of the research questions.

5.2.1. Research Question 1

i. How do barbell displacement and Δ PE of the body segments vary between single repetitions at the same or different barbell masses?

This research question was established to examine the variation of repetitions at a given barbell mass and the differences in variation and systematic bias due to increasing barbell mass, without the confounding effect of consecutive repetitions. To address the broad question, three sub-questions were derived to examine these aspects on single participant and group levels.

a) What is the variation of BD and body Δ PE for an individual within a single barbell mass condition?

For the back squat, variation (CV) ranged from values that could be considered low (0.4 and 0.6 % for BD and body Δ PE, respectively) to values that were up to 12.5 times greater (4.5 and 5.0 %, respectively). For the hang clean, the results produced similar conclusions, although CV values are not directly comparable. Some individuals displayed low variation in single conditions (0.7 and 0.6 % CV for BD and body PEW, respectively), whilst others displayed greater magnitude of CV (6.0 and 8.0 %, respectively).

Due to the theoretical issues with defining an acceptable threshold of variation (Atkinson and Nevill, 1998), CV values cannot be definitively concluded to represent high or low variation. However, interpreting a CV of 0.4 % (P10, BS92; 768 ± 3 mm) in its situational context leads to the conclusion that this value represents low variability, given the complexity and displacement range of the back squat. This would lead to low error in the estimation of barbell Δ PE, if BD was assumed constant between repetitions at the same barbell mass. As an

individual's variation increases in magnitude from this level, accuracy of the assumption of constant BD, body Δ PE or body PEW falls. Therefore, this reduction in accuracy is clearly indicated by increased CV but the level of acceptability for practical use, given the context, remains subjective.

- b) *What is the difference in magnitude and variation of BD and body Δ PE for an individual between barbell mass conditions?*

For some individuals, significant reductions in each variable for both exercises occurred due to increased barbell mass. Other individuals displayed no significant differences for BD and body Δ PE in the back squat and body PEW in the hang clean, thus indicating only a small degree of error would be created by assuming these variables constant between different barbell masses. For both back squat and hang clean, no patterns of CV change due to barbell mass were detected for either variable.

Some individual comparisons did not reach statistical significance, perhaps due to greater variance around the mean when similar differences in magnitude existed (e.g. BS70 vs. BS92 for P3). This is an important point about the interaction of the two statistical methods utilised in this investigation. Significant systematic bias cannot on its own signify a large degree of error and vice versa. Indeed very low variation may lead to significant bias being detected when actual between condition differences are lower than another individual for whom greater variation prevents higher between condition differences reaching significance. It is within this context that both of these statistical assessments were required for overall conclusions to be drawn. For example, for the back squat, it is P10 which would be expected to show the lowest degree of error if barbell displacement was assumed constant for single repetitions to represent Δ PE as VL as they had the lowest variation but also no systematic bias (Table 4.1). Conversely, P3 was an example of the opposite situation where higher variation around condition mean values prevented significant bias being recorded.

It was concluded that the effect of barbell mass on variation and systematic bias of BD and body Δ PE or PEW should be assessed on an individual case basis due to the variety of inter-individual responses.

- c) *Is there a systematic difference in magnitude and variation of BD and body Δ PE for a group across barbell mass conditions?*

There were significant reductions in BD and body Δ PE found at the group level in the back squat, although the location of significance could only be determined for the latter variable (BS70 > BS92). For the hang clean, BD was significantly lower between each condition as barbell mass increased, whilst there was no significant effect detected for body PEW. Irrespective of specific post-hoc comparisons, overall group-level statistical significance indicates that assuming variables constant between barbell masses is not accurate without direct assessment, even for experienced resistance trained individuals.

Overall, the data pertaining to research question 1 showed that for certain individuals it could be assumed that BD and body Δ PE were constant between single repetitions of the back squat at the same and different barbell masses. This validated the notion of considering VL and SMVL_{BS} as proportional representations of barbell Δ PE and total Δ PE, respectively. However, due to inter-individual differences, the efficacy of these assumptions must be considered on a case-by-case basis for this exercise. The systematic bias in BD at group and individual levels in the hang clean meant that the same assertions cannot be made for this exercise.

5.2.2. Research Question 2

ii. How do barbell displacement and Δ PE of the body segments vary between three sets of consecutive repetitions at a moderately heavy barbell mass?

The second research question was designed to examine the influence of consecutive repetitions on variation and systematic bias at a constant barbell mass. To address this broad overall question, four sub-questions were developed to examine variation and systematic bias within and between sets, as well as on single participant and group levels. Comparisons were also made to single repetitions at the same barbell mass.

- a) *What is the variation of BD and body Δ PE for an individual in a single set of consecutive repetitions?*

As with single repetitions, CV values indicated that variation of BD (back squat CV = 0.6 to 4.2 %; hang clean CV = 1.3 to 6.2 %), back squat body Δ PE (CV = 0.8 to 4.4 %) and hang clean body PEW (CV = 2.5 to 12.4 %) ranged from

values that were concluded to represent low variation to those that were considerably greater in magnitude, although a threshold of acceptability could not be determined.

- b) What is the difference in magnitude and variation of BD and body Δ PE for a group for a single set of consecutive repetitions in comparison to single repetitions at the same moderate barbell mass?*

Group significant effects were established between BS82 and repetitions in BSS1 for BD and body Δ PE, although the location of significance could only be determined for the latter variable (BS82 > BSS1 repetition 1). For the hang clean, significant differences between HCS1 and repetitions in HC82 were found for BD (HC82 > HCS1 repetition 1). Conversely, no differences in body PEW were found between any repetition in HCS1 and HC82. There was no relationship between CV of single repetitions and consecutive repetitions at the same or different barbell masses.

Data showing first repetition reduction of BD and body Δ PE in the back squat and BD in the hang clean presents a new insight into the impact of set and repetition schemes on kinematic factors related to external training load. Previously, it has been reported by Willardson et al. (2012) that performing three sets of consecutive repetitions to failure of the back squat with a constant external mass led to progressively fewer repetitions being completed. Whilst no kinematic data were reported, these findings showed negative performance effects of additional repetitions. Similar negative effects of additional repetitions have been found for the hang clean (Hardee et al., 2013). The contrary findings presented in this report could be attributed to an anticipatory effect, where the participant is initially attempting to conserve energy by reducing BD. Alternatively, it may be due to an acute familiarisation effect where the participants are reducing BD to allow for readjustment to moving with a large external mass. Irrespective of cause, coaching cues could be implemented during the session with a specific focus on ensuring full displacement range on the first repetition to negate these effects as they cannot be due to physical or physiological limitation.

- c) What is the difference in magnitude and variation of BD and body Δ PE for an individual between three sets of consecutive repetitions?*

For the back squat, significant differences were only detected for two participants (P4 & P9) for both variables. In the hang clean, only one individual (P5) showed a significant difference for BD. These results indicated that, for most individuals, additional sets of consecutive repetitions in the back squat and hang clean did not result in systematic differences in mean BD, body Δ PE or body PEW. There were no consistent within-individual patterns of variation between the three sets of consecutive repetitions for either variable or exercise.

d) Is there a systematic difference in magnitude and variation of BD and body Δ PE for a group between three sets of six consecutive repetitions?

Significant effects of repetition within a set were identified for BD and body Δ PE during the back squat over the three sets. This highlighted that when applying the assumptions relating to VL and $SMVL_{BS}$ for sets of consecutive repetitions, they cannot be considered accurate without individual assessment or additional coaching cues that could potentially reduce within set differences. For the hang clean, there was a significant interaction effect of set and repetition for BD, supporting the evidence from earlier research questions that showed this variable cannot be assumed constant. Body PEW in the hang clean showed no significant differences on any comparisons. There were no systematic differences in CV between sets for either variable in each exercise.

The overall conclusion from research question 2 is that for some individuals, assuming BD and body Δ PE or body PEW constant over three sets of six consecutive repetitions of the back squat and hang clean may lead to a low degree error. However, as with the single repetition conditions, the group evidence indicated that these assumptions should be assessed on an individual basis, especially within a set of the back squat and over the course of multiple sets of hang clean.

5.2.3. Research Question 3

Can a standardised reference value (BMF) be used to calculate an accurate representation the Δ PE of the body segments in addition to the Δ PE of the barbell for the resistance training quantification method System Mass VL?

This question was devised to examine the validity of using a novel method to incorporate the Δ PE of the body segments with that of the barbell in a practically feasible way. The first three sub-questions concerned examining variation and

systematic bias of the proposed variable, BMF, for the same comparisons as BD and body Δ PE in research question one. The fourth and fifth sub-questions were only addressed for the back squat due to the bias in BD between barbell masses and greater inter-individual differences in magnitude of BMF_{PEW} for the hang clean. These final two sub-questions address the practical implications of the accuracy of the SMVL method.

- a) What is the variation of BMF for an individual within a single barbell mass condition?*

The CV of BMF ranged from 0.3 to 1.3 % for the back squat and from 1.3 to 5.9 % for BMF_{PEW} in the hang clean, leading to the conclusion that variation of these variables can be low within a barbell mass condition for either exercise. The differences in mean value of back squat BMF and hang clean BMF_{PEW} values meant that the CV values are not comparable between exercises. However, absolute variation (SD) was greater for the hang clean, despite its smaller mean and thus indicated that BMF was less variable than BMF_{PEW} .

- b) What is the difference in variation and magnitude of BMF for an individual between barbell mass conditions?*

No pattern of effects of barbell mass on variation of BMF or BMF_{PEW} were detected for either exercise. Conversely, six (from 10) participants for the back squat and seven (from 8) for the hang clean showed individual significant differences between barbell mass conditions in mean BMF and BMF_{PEW} , respectively. Clarity on the practical meaning of the between barbell mass and individual differences in BMF for the back squat is provided by sub-question d). For the hang clean, BMF_{PEW} was barbell mass specific, although these differences were due to changes in BD, not body PEW. Additionally, a greater between-participant range of hang clean BMF_{PEW} compared with group value indicated that body PEW during the hang clean was not consistent for the group. The greater variability, systematic bias and inter-individual differences for hang clean BMF indicates that the SMVL_{HC} method is not appropriate for use with this exercise.

- c) Is there a systematic difference in magnitude and variation of BMF for a group of participants across barbell mass conditions?*

Significant differences in BMF and BMF_{PEW} between barbell mass conditions were found for both exercises, whilst there was no significant systematic bias found in CV for either exercise. For the back squat, the differences between conditions in BMF were broadly representative of decreases in body ΔPE in this exercise. Despite statistical differences, the practical meaning was low and is demonstrated by data pertaining to sub-question d).

For the hang clean it was highlighted by the previous sub-question that changes in hang clean BMF_{PEW} were due to BD, and not body PEW, changing due to barbell mass. Therefore, it was deemed that BMF_{PEW} was not valid for the hang clean and further data were not presented.

- d) *How accurate is using the group mean BMF value from the single repetition condition with moderate barbell mass to estimate total ΔPE for consecutive repetitions?*

The degree of accuracy of estimation of back squat total $\Delta\text{PE}_{\text{BMF}}$ for one repetition was 0 ± 8 J for all ten participants' three sets of six consecutive repetitions. The mean value falsely shows complete agreement between total ΔPE and total $\Delta\text{PE}_{\text{BMF}}$ however, the small SD of actual errors confirms good absolute accuracy as 68.2 % (122 repetitions out of 180) were smaller than 0.7 % of the group mean total ΔPE (1159 J). This estimation used measured BD from each repetition combined with the group mean barbell mass specific BMF value from the single repetitions. It therefore identified the error solely due to use of a standard BMF value, and indicates that the practical meaning of individuals variation and inter-individual differences in back squat BMF value were low. This methodology provides an accurate method to estimate total $\Delta\text{PE}_{\text{BMF}}$ if BD can be measured for every repetition.

- e) *Can a newly defined method of RT quantification (termed System Mass VL) be used to calculate an accurate representation of total ΔPE for consecutive repetitions?*

When BD and BMF were assumed constant, the degree of error of estimation of back squat total $\Delta\text{PE}_{\text{BMF}}$ rose to 27 ± 50 J for one repetition. For the 18 repetitions this resulted in a mean over estimation of total ΔPE by 491 ± 785 J, or 2.5 ± 3.5 % of the cumulative mean value. The increase in error is accounted for by the difference in individual mean BD in BS82 (the value used to estimate

total ΔPE_{BMF}) and the actual BD from each repetition in each set. Therefore, assessment of the mean differences in BD between sets of repetitions provides an indication error due to assumption of constant BD.

The directly proportional relationship between total ΔPE_{BMF} and $SMVL_{BS}$ determines that the accuracy of estimation of total ΔPE_{BMF} for the back squat described above is also applicable to $SMVL_{BS}$. However, as outlined in previous research questions it is recommended to individually assess athletes or participants due to considerable inter-individual variation in BD and consequently, error in $SMVL_{BS}$.

For the back squat, measurement of BD for every repetition provides more accurate estimate of total ΔPE_{BMF} . If this is not possible then $SMVL_{BS}$ may also provide and accurate representation of ΔPE . It is acknowledged that calculation of ΔPE is not a complete description of the energetics of RT, excluding kinetic energy and therefore the temporal aspect of exercises performed. This deficiency has been demonstrated by (Crewther et al., 2008) where a 67 % difference in mass displaced resulted in only a 29% difference in work done. If this limitation is acknowledged then greater clarity can be achieved in interpretation of acute and chronic responses to RT when quantified by VL. For example, when VL is considered as ΔPE , it is unsurprising that studies using varied training modalities (power, strength and hypertrophy) cannot conclusively relate quantity of RT to subsequent responses. Empirical investigations require as much detail as possible in the laboratory setting to overcome this issue, whilst the currently proposed methodology provides improved clarity and understand of measures available in the field.

Due to the greater variation and systematic bias between conditions for the hang clean, the required assumptions cannot be applied to this exercise. Although it is not possible to determine the causes of the differences in hang clean BD, consideration of the design of the human motor system may elude to possible explanations. It was contended by Bartlett et al. (2007) that the human body is orientated to achieve the outcome goals of tasks posed to it. In the present scenario of the hang clean, success is determined by whether the barbell is caught on the front of the shoulders without dipping into a full Olympic squat position. As the intensity of an activity increases, it has been suggested that control of the task is determined to a greater extent by the mechanical qualities of the active contractile and passive elements of the locomotion system than by precise

conscious control of neural inputs to this system (Full and Koditschek, 1999). Consequently, at higher relative intensities, the participant is potentially less able to specifically dictate the key determinant of a successful outcome (height of the barbell). Instead, they have to apply maximal effort early in the movement and rely on the fact that the capacity of their mechanical systems is sufficient to achieve the desired outcome. The consequence is that at the highest barbell mass, the mechanical system will be least able to displace the barbell vertically and as a result successively lower BD will occur. Overall, the mechanical differences of the hang clean suggest alternate measurement and interpretation of quantitative RT information gathered for this exercises must be considered.

5.3. Measurement Considerations

Every plausible effort was made to ensure the accuracy of measurement of the displacement of the barbell during each exercise. The marker configuration employed accounted for dipping of one side of the barbell, a potential source of error if only a single marker on the end of the barbell was used. Combined with very little occlusion occurring for the barbell markers, the overall accuracy of BD measurements is considered good. Ideally, markers would have been attached to either end of the barbell to make estimation of its CoM location simpler. As this was not possible, the mean of 6 methods of estimating the centre of rotation location at the sleeve end was combined with measurements from one end of the barbell. Whilst the six calculations generally agreed, they did not match exactly. For the back squat the mean of CV from each trial of the estimated sleeve end vertical coordination values was equal or below 0.5 % for all participants, and for the hang clean all mean values were equal or below 0.7 % (Table 4.7). Considering the average displacement range of the barbell in the back squat (657 ± 66 mm) this would lead to around a 3 mm error in $Z_{CoR-Est}$, which would be reduced further when overall barbell CoM was calculated.

The kinematics of the body were measured to form an eight segment unilateral model with bilateral symmetry assumed. The back squat and hang clean are technically bilaterally symmetrical, although slight side-to-side differences in movement pattern could lead to errors, but these would likely be of a negligible degree. All repetitions were visually monitored by the author who is an accredited strength and conditioning coach with no noticeable asymmetries being detected.

The use of segment inertial parameters provided by de Leva (1996a) meant that anthropometric differences between participants, other than body mass, will not have been accounted for in body Δ PE values. The lack of individualisation of CoM location is likely to only cause a very small degree of error, as it was only the vertical displacement of each segment that was required for the Δ PE calculations. The effect of differential distribution of body mass between participants segments could potentially have been a source of greater inaccuracy, although these would have only affected group comparisons. As the primary conclusions are based on intra-individual variation and bias between repetitions and conditions, the influence of this source of error on the findings was reduced.

The vertex of the head was one of the designated anatomical land mark from which inertia parameters were calculated by de Leva (1996a). Due to limitations in the experimental set up and marker positioning on this landmark, the tragus of the ear had to be considered representative of the motion of the CoM of the head. Whilst not fully aligned with the definitions of de Leva (1996a), the head underwent little motion during either the back squat or hang clean that was not linear displacement in the vertical axis. Consequently, this adjustment to quantifying the kinematic motion of the head is not considered to adversely affect the accuracy of the results.

Generally, the quality of the kinematic data from the body was good, although for some participants there were issues with marker occlusion. For the back squat, the acromion marker presented the most problems based on inter-individual variability in barbell placement. However, the occlusion always occurred mid-way through the upward phase so as the overall change in Δ PE from the start to end of the upward movement phase was of concern, the results were not affected. This was aided as the shoulder joint does not undergo any major angular displacement during the back squat. In the hang clean, analysis of body PEW only up to the end of the 1st upward phase, meant there were very few issues with marker occlusion. In all trials, the barbell covered the subclavicular notch marker for a few samples as it passed vertically, as with the acromion marker for the back squat this did not affect the analysis. After the end of the 1st upward phase, several markers became occluded until the end of the trial, which meant that body PEW could not be calculated beyond this point.

Considering the distinct differences between 1st upward, downward and 2nd upward phases for BD in the hang clean across barbell masses, examination of body PEW over

these phases may reveal similar differences. The analysis was not performed due to the problems of marker occlusion identified previously. Further suggestion of potentially relevant determinants of the mechanical stimuli of the hang clean being missed by the current analysis are provided by the observation that the knee angular kinematics showed a sudden flexing prior to maximum flexion in the downward phase (see Figure 3.6, circled). It is likely that this rapid flexion is involved in decelerating the barbell prior to the 2nd upward phase, and it could be hypothesised that this sudden movement causes eccentric muscular contraction, known to cause muscle damage (Friden et al., 1983). Therefore, whilst not directly related to determining external training load in relation to the intended neuromuscular adaptation, the latter portions of the hang clean movement sequence could have a contribution to overall physiological or mechanical stress. As highlighted earlier in the discussion, measurement of total systemic stress was outside of the scope of the present investigation. However, such measurement would be interesting as this is likely to be one of the key indicators for overtraining.

The rationale for using the alternative terminology of PEW has been discussed at several points. An alternative calculation method that would have allowed the Δ PE terminology to be utilised for the hang clean would have involved continuous calculation of Δ PE (including barbell and body) over the upward phase, with the peak value taken as the measurement of RT performed. However, this would not have permitted independent analysis of the maximum Δ PE of the barbell and the body due to the lack of temporal synchronicity in their maximum values. In fact, it would have neglected some important changes in Δ PE of the body that occur prior to maximum barbell Δ PE.

As stated in the methodology, three sets of 6 consecutive repetitions were considered to be a training scheme comparable to those utilised by athletes. However, it could be contended that whilst the number of repetitions per set is similar, athletes may often perform more sets of this repetition range (frequently up to six sets). Consequently, performing additional sets may have elicited different between-set, within-set or interaction effects. This limitation is acknowledged, although based on the conclusion that each individual should be assessed for variation and systematic bias it should be addressed by future researchers or practitioners who wish to examine more than three sets.

It has been highlighted at several points that CV cannot be definitively concluded to be high or low, as it is impossible to set a reference threshold for this statistic (Atkinson and Nevill 1998). As a result, the magnitude of variation was interpreted using its context as a reference, for example, a SD of 3 mm for five repetitions of the back squat with mean BD of 768 mm could only be concluded to show low variation given the complexity of intra- and inter- muscular coordination required to achieve the movement. With the goal of the investigation being to determine error in estimation of ΔPE , if BD is assumed constant, this level of variation (0.4 % CV) will clearly lead to a low degree of error. However, as demonstrated by the estimations of total ΔPE for back squat, CV from single repetitions does not directly relate to the magnitude of error calculated.

5.4. Practical Implications

For the back squat, the small error found when estimating total ΔPE_{BMF} using measured BD and the group mean BMF value shows this method could be implemented in research or field settings with a good degree of accuracy. Linear position transducers that are commercially available (e.g. GymAware, Kinetic Performance Technology, Australia) at reasonable prices provide reliable methods to measure BD during training sessions. Use of this technology would allow valid and accurate inclusion of body mass in the quantification of external training load, calculated as ΔPE . Beyond the back squat, the mechanically valid basis of BMF provides a methodology that can be replicated on additional exercises to broaden the scope of possible applications of this RT quantification process.

If direct measurement of BD for every repetition of the back squat over time is not possible, then the SMVL method can provide an accurate alternative. If utilised, it is suggested to assess systematic bias between barbell masses for each individual with a linear position transducer or similar device. This is due to the association of error in this method to differences between the standard value of BD used and actual value. To ensure the validity of an assessment, it is recommended that it occurs in a similar training phase (weekly, monthly or yearly) to which the training quantification will be utilised to control for acute and/or chronic fatigue effects or seasonal differences in training status. For best practice, the assessment should also be repeated as frequently as noticeable technical changes occur in movement pattern.

The assessment is recommended to be comprised of two sets of consecutive repetitions at two or more relative barbell mass levels that are utilised in training. Comparisons can be made between sets at the same barbell mass or between different barbell masses. Differences between the means of any compared sets, expressed as a percentage of the first of the means, are strongly related to error due to assumption of constant BD in SMVL. The relationship is not direct (i.e. a 5 % difference in means does not equal a 5 % error) due to small degree of error created by using a standard BMF value, but there is general agreement between these values. It should be noted that high levels of variation in any set of the assessment confound the comparison of means. In the present sample, the greatest variation detected in a set of consecutive repetitions was 4.2 %. Although a definitive threshold of acceptability cannot be determined, it is stressed that minimisation of variation will provide more accurate data.

Should notable differences between sets of repetitions be observed in the assessment then coaching interventions can be implemented. Standardisation of movement range by utilising physical external cues (e.g. a box or bar to denote required squat depth) would improve the accuracy of the estimation of ΔPE and negate the need for reassessment of BD range over a season. Alternatively, verbal coaching cues may be given to facilitate standardisation of depth, however, there would be a lower degree of certainty that degree of error had been reduced without taking measurements.

Implementation of the field assessment described above allows an individual's error in SMVL between two sets of barbell back squat to be estimated. Consequently, this value can be utilised when forming conclusions based on comparisons of external training load considering SMVL as a representation of the ΔPE of the barbell and the body.

5.4.1 Perspectives

For any practitioner or researcher looking to determine the amount of RT any individual performs there are important implications from this thesis. Those concerned with highly accurate measurements of the total amount of training an athlete or participant has performed, it is acknowledged that SMVL does not provide a complete measurement tool. However, the data presented here shows that it can be an accurate measure for the back squat if velocity of movement is not important. Consequently, if either maximum strength or hypertrophy is the key training goal, then the SMVL method is suggested to be appropriate. The recommended assessment method allows for estimation of any

given individuals degree of error to inform decisions made from gathered data. If this is not possible, then the reference value for SMVL in this study of $2.5 \pm 3.5 \%$ provides the first report of accuracy of this type of training quantification.

If the specific accuracy of measurement of the volume of training is less important, then the reported findings are also of interest. Using the BMF value, a considerable proportion of the total mass displaced in the back squat (typically 30-36 %) can now be accounted for in a scientifically valid manner, which is also practically applicable in the applied training environment.

For the hang clean, the findings showed that the SMVL method was not appropriate for this exercise. The VL method could still be utilised as a general measure of training performed, but it is not possible to accurately make assumptions about the consistency of execution of the hang clean.

5.5. Future Research

Development of RT quantification methods that can allow for a much more detailed examination of external training load and its relation to the mechanical stimuli that elicit internal training load and subsequent adaptation are required. Measures that describe the energetics of the barbell-body system, such as total mechanical work, involve considerable practical and methodological issues, but this approach would provide advancement in relation to the currently discussed methods. However, as the detail of training prescription increases to address evermore targeted sporting performance needs, even accurate systemic measures cannot provide the complete description of training performed. Inverse dynamic approaches are among the most detailed methods currently available, but even these can only compute net joint actions and not the kinetics of specific anatomical structures, often the target of training interventions. Much endeavour is required to advance knowledge of this topic to provide useful information to applied practitioners.

The second area that it is suggested future research should focus on is establishing the relationships between external training load and acute and chronic responses to RT, as well as the factors that influence these processes. Examination of these links should be performed on the basis of clear understanding of the mechanical aspects of RT that are being measured. Combined with data on the error that to be expected in the quantification of external training load, more detailed conclusions can be drawn on the

required dose of various forms of RT to particular elicit neuromuscular adaptations. Moreover, a greater understanding of the resolution on which judgements about training prescription can be made (i.e. can it be demonstrated that one extra set of an exercise per week will make a difference in a month or is it and extra training session per week required over 3 months) could be established by further work.

5.6. Thesis Conclusion

This thesis has examined the scientific validity of widely utilised methods of quantifying external load in RT. The data revealed that whilst using ΔPE as the underpinning mechanical principle for these methods, their validity is subject to intra-individual variability in movement execution. Having established clearly defined criteria within which the outlined methodology is appropriate, the importance of understanding the purpose for which any measurement metric is employed in relation to the training goals is emphasised. Indeed, the rationalised mechanical basis for combination of the energetics of the barbell and body mass offers a framework from which further research can examine the relationships between training load and neuromuscular adaptation. If development of this field of research continues, then this information will increase the efficiency and likelihood of success in realising the intended outcomes of RT to improve sporting performance.

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APPENDIX 1: Hang Clean Results

Overall the error of estimated total ΔPE using the BMF_{PEW} method to calculate the body PEW component was -5 ± 14 J (Figure A1.1). Total ΔPE values for all the repetitions in the three sets for each participant at 82 % of 1RM are given in Figure A1.2.

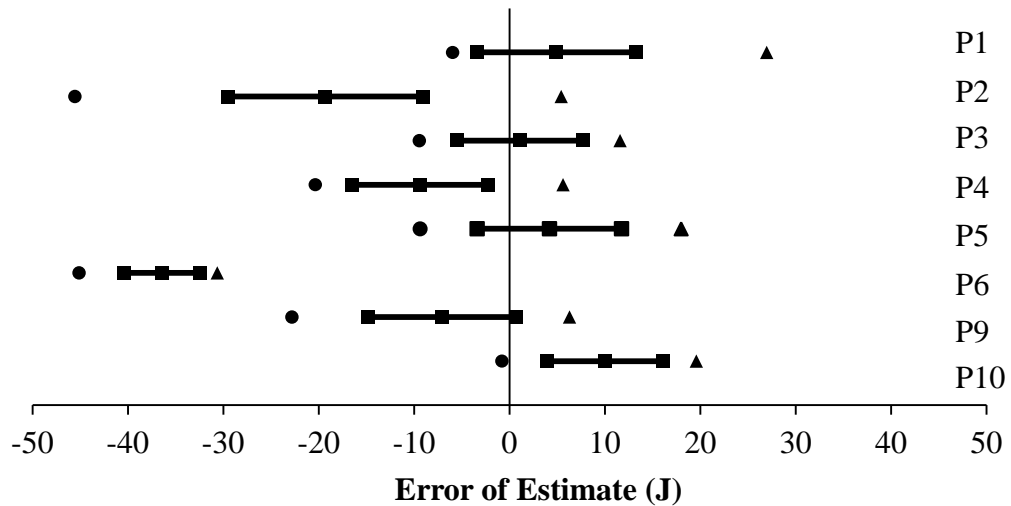


Figure A1.1. Error of estimated total ΔPE for all repetitions in HCS1, HCS2 and HCS3 for each participant using the BMF_{PEW} method. Mean ($\pm SD$) are represented by closed boxes and minimum and maximum range are represented by closed circles and triangles respectively.

The overall mean error of estimated total ΔPE using group mean BMF_{PEW} and individual mean BD from BS82 was 9 ± 39 J. The mean cumulative total ΔPE from all repetitions performed by each participant was 10608 ± 2721 J while the cumulative estimated value was 10745 ± 2622 J (Figure A1.3). There was no significant difference between the measured and estimated values ($p = 0.464$). The mean of individual differences between measured and estimated values was 137 ± 500 J. This related to a mean error equivalent to the ΔPE value of 0.2 ± 0.7 repetitions (range -1.4 to 0.9) or 1.6 ± 4.4 % of the mean of the sum of measured total ΔPE . The group mean $SMVL_{HC}$ for one repetition was 100 ± 21 a/u and for all repetitions performed was 1561 ± 424 a/u. Note that all of these values account for the different number of repetitions performed by the participants.

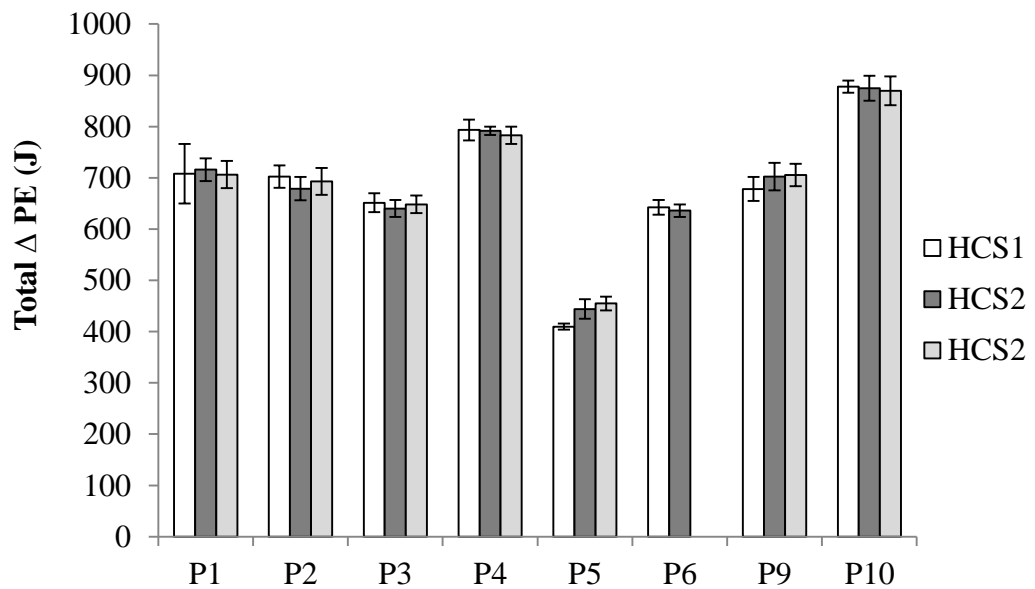


Figure A1.2. Mean (\pm SD) total Δ PE in HCS1, HCS2 and HCS3 for all participants.

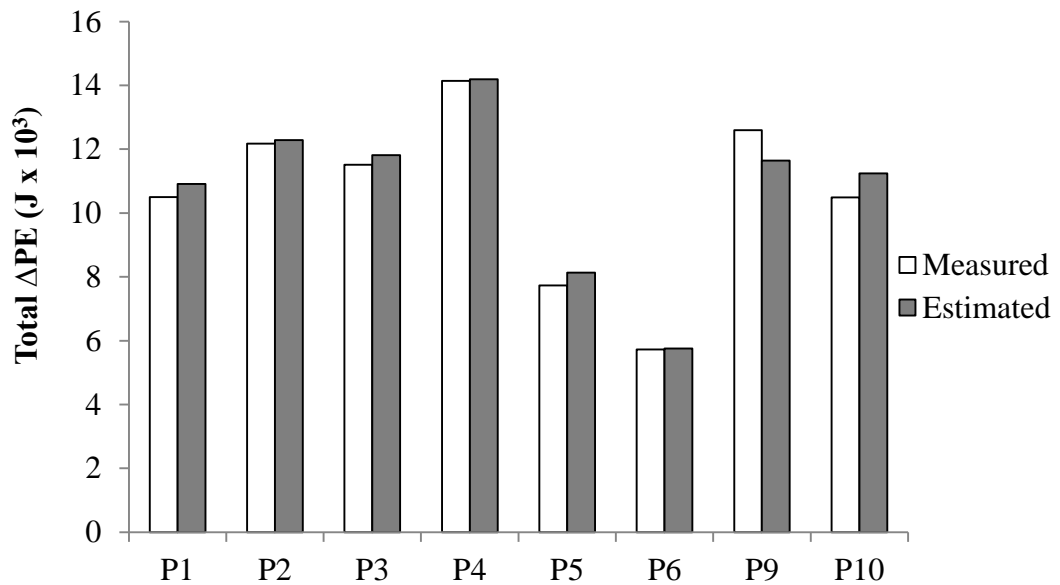


Figure A1.3. Total Δ PE for the three sets of six consecutive repetitions from the actual measured values and estimated using individual participant BD and group mean BMF values from HC82.